

# The nuclear and extended infrared emission of the Seyfert galaxy NGC 2992 and the interacting system Arp 245

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## ABSTRACT

We present subarcsecond resolution infrared (IR) imaging and mid-IR spectroscopic observations of the Seyfert 1.9 galaxy NGC 2992, obtained with the Gemini North Telescope and the Gran Telescopio CANARIAS (GTC). The N-band image reveals faint extended emission out to  $\sim 3$  kpc, and the PAH features detected in the GTC/CanariCam 7.5–13  $\mu\text{m}$  spectrum indicate that the bulk of this extended emission is dust heated by star formation. We also report arcsecond resolution MIR and far-IR imaging of the interacting system Arp 245, taken with the Spitzer Space Telescope and the Herschel Space Observatory. Using these data, we obtain nuclear fluxes using different methods and find that we can only recover the nuclear fluxes obtained from the subarcsecond data at 20–25  $\mu\text{m}$ , where the AGN emission dominates. We fitted the nuclear IR spectral energy distribution of NGC 2992, including the GTC/CanariCam nuclear spectrum ( $\sim 50$  pc), with clumpy torus models. We then used the best-fitting torus model to decompose the Spitzer/IRS 5–30  $\mu\text{m}$  spectrum ( $\sim 630$  pc) in AGN and starburst components, using different starburst templates. We find that, whereas at shorter mid-IR wavelengths the starburst component dominates (64% at 6  $\mu\text{m}$ ), the AGN component reaches 90% at 20  $\mu\text{m}$ . We finally obtained dust masses, temperatures and star formation rates for the different components of the Arp 245 system and find similar values for NGC 2992 and NGC 2993. These measurements are within those reported for other interacting systems in the first stages of the interaction.

**Key words:** galaxies: active – galaxies: nuclei – galaxies: photometry – galaxies: spectroscopy – galaxies: group (Arp 245) – galaxies: individual (NGC 2992, NGC 2993).

## 1 INTRODUCTION

Active galactic nuclei (AGN) are powered by supermassive black holes (SMBHs), which release enormous quantities of energy in the form of radiation or mechanical out-

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flows to the host galaxy interstellar medium. This feedback is fundamental to the formation and evolution of the host galaxies (Hopkins & Quataert 2010). On the other hand, galaxy mergers and interactions or secular processes can generate gas inflows to the nuclear regions of galaxies, potentially triggering both AGN and central starbursts (SB; Hopkins et al. 2008). It has been proposed that the triggering mechanisms might depend on AGN luminosity (e.g. Ramos Almeida et al. 2012; Treister et al. 2012), with high-luminosity AGN (e.g. quasars and powerful radio galaxies) being more commonly triggered by galaxy interactions and low-to-intermediate luminosity AGN (e.g. Seyferts and low-ionization nuclear emission-line regions; LINERs) by disk instabilities, galaxy bars, etc. However, this dependence is not univocal, and examples of both low-luminosity AGN in interacting systems and quasars in isolated and morphologically undisturbed galaxy hosts are also found in different galaxy samples (Lípari et al. 2004; Serra et al. 2006; Bessiere et al. 2012).

Seyfert galaxies are intermediate-luminosity AGN, characterized by a very bright unresolved nucleus generally hosted by a spiral galaxy (Adams 1977). They can be classified as type 1 or type 2 depending on orientation, according to the unified model (Antonucci 1993). This scheme proposes that there is dust surrounding the active nucleus distributed in a toroidal geometry, which obscures the central engines of type 2 Seyferts, and allows a direct view in the case of type 1. The dusty torus absorbs the intrinsic AGN radiation and, then, reprocesses it to emerge in the infrared (IR), peaking in the mid-IR (MIR;  $\sim 5\text{--}30\ \mu\text{m}$ ).

MIR observations of the nuclear regions of active galaxies allow to study the emission of dust heated by the AGN, but also by star-formation (SF) when present (e.g. Radomski et al. 2003; Packham et al. 2005; Esquej et al. 2014; Alonso-Herrero et al. 2014). Prominent features in the MIR spectrum of Seyfert galaxies are the  $9.7\ \mu\text{m}$  silicate band and the Polycyclic Aromatic Hydrocarbon (PAH) emission bands, although the latter can be diluted by the bright AGN continuum, and therefore they have lower equivalent widths (EWs) than those of non-active star-forming galaxies (see e.g. Alonso-Herrero et al. 2014; Ramos Almeida et al. 2014). The high angular resolution is crucial to correctly separating the nuclear emission from the foreground galaxy emission, as the MIR-emitting torus is very small ( $r < 10\ \text{pc}$ ; see e.g. Tristram et al. 2009; Bartscher et al. 2013).

To contribute to the understanding of the relation between nuclear activity, SF, torus properties and circumnuclear emission, here we use IR and optical imaging and MIR spectroscopy of the Seyfert galaxy NGC 2992. This inclined spiral galaxy ( $b/a=0.31$ ; de Vaucouleurs et al. 1991) is located at a luminosity distance of 36.6 Mpc and it is part of the interacting system Arp 245. This system is formed by NGC 2992, the spiral star-forming galaxy NGC 2993 (Usui, Saito, & Tomita 1998) and the tidal dwarf galaxy Arp 245 North (hereafter Arp 245N; Duc et al. 2000). Two bright tidal features connect these three galaxies, suggesting that the system is in an early stage of the interaction (Duc et al. 2000). We selected the Arp 245 system for this IR study, and the galaxy NGC 2992 in particular, because of the plethora of multiwavelength data available in the literature, and because we have new far-IR (FIR) observations from the

Herschel Space Observatory as well MIR data from CanariCam on the 10.4 m Gran Telescopio CANARIAS (GTC). NGC 2992 was observed with these telescopes because previous MIR imaging data revealed extended emission on nuclear scales, possibly related to the interaction with the other galaxies in the Arp 245 system. Our aim is to study the origin of this IR extended emission by combining the existing and the new IR observations. See Section 2 for a detailed description of the observations employed here.

NGC 2992 is classified as a Seyfert 1.9 in the optical, although it has changed its type between Seyfert 1.5 and 2 in the past (Trippe et al. 2008). It also exhibited huge variations in the X-rays (factor of  $\sim 20$ ; Gilli et al. 2000) and in the IR as well (Glass 1997). The IR variations were probably caused by a retriggered AGN and by different stages of the rebuilding of the accretion disk, with the disk rebuilding estimated to range between 1 and 5 years (Gilli et al. 2000). Besides, Glass (1997) found flux variability in the near-IR (NIR), and reported a fading of the source from 1978 to 1996, apart from a strong outburst in 1988. The galaxy shows a thick dust line at  $\text{PA} \sim 25\text{--}30^\circ$ , measured from north to east, which has been shown to be affecting the emission line profiles in the optical (Colina et al. 1987).

NGC 2992 also has evidence for intense SF (Quillen et al. 1999), with large-scale outflows observed in  $\text{H}\alpha$ ,  $[\text{O III}]\lambda 5007\ \text{\AA}$  and soft X-rays, driven either by jets or by a SB (Colina et al. 1987; Colbert et al. 1998). In fact, the molecular gas emission in NGC 2992 could be excited by processes associated with local star formation (Quillen et al. 1999). The outflow component is distributed in two wide cones (Colina et al. 1987; Durret & Bergeron 1987; Colbert et al. 1996; Allen et al. 1999; Veilleux, Shopbell, & Miller 2001), with the geometry of the biconical outflow being such that the southeastern cone is in front of the galaxy disk and the base of the north-western outflow is behind it. Apart from the two main kinematic components of the ionized gas (rotation+outflow), an additional component is required to explain the departure of the ionized gas from the gravitational motion defined from the stars. This component would be related to the AGN, and not to the interaction (García-Lorenzo, Arribas, & Mediavilla 2001). The hidden Seyfert nucleus is probably located at the apex outflow origin and at the center of the bulge, but it does not seem to coincide with the kinematic center of the disk (García-Lorenzo, Arribas, & Mediavilla 2001).

Although NGC 2992 has been observed at several wavelengths, up to date there is not any detailed high resolution IR analysis of this active galaxy or of the entire system. Here we present a complete IR study of the interacting system Arp 245, focusing on NGC 2992. Section 2 describes the observations and data reduction. The main results, including a compilation of IR fluxes, are presented in Section 3. We explore different methods to recover the nuclear emission from low angular resolution data in Section 4. We derive relevant physical parameters of the dust emission in Section 5. Finally, in Section 6 we present the discussion and in Section 7 we summarize the main conclusions of this work.

Throughout this paper we assumed a cosmology with  $H_0=73\ \text{km s}^{-1}\ \text{Mpc}^{-1}$ ,  $\Omega_m=0.27$ , and  $\Omega_\Lambda=0.73$  for the Arp 245 system. This cosmology provides a luminosity dis-

tance of 36.6 Mpc and a spatial scale of 174 pc'' (from the NASA/IPAC Extragalactic Database; NED).

## 2 OBSERVATIONS

In this section we describe all the observations analyzed in this work, which we divide in subarcsecond and arcsecond resolution data. Subarcsecond data are from 8-10m-class ground-based telescopes and from the Hubble Space Telescope (HST), which allow us to resolve the innermost regions of the galaxies. Arcsecond resolution data correspond to observations taken with the Spitzer Space Telescope and the Herschel Space Observatory, which have lower spatial resolution but higher sensitivity. Details of the observations are summarized in Table 1.

### 2.1 Subarcsecond resolution data

#### 2.1.1 MIR Gemini/MICHELLE observations

Two images were taken in the N' ( $\lambda_c=11.2 \mu\text{m}$ ) and Qa ( $\lambda_c=18.1 \mu\text{m}$ ) filters using the instrument MICHELLE (Glasse, Atad-Ettdgui, & Harris 1997) on the 8.1 m Gemini-North Telescope. MICHELLE is a MIR (7-26  $\mu\text{m}$ ) imager and spectrograph, which uses a Si:As detector, covering a field-of-view (FOV) of  $32'' \times 24''$  on the sky. Its pixel scale is  $0.1005''$ . The standard MIR chopping-nodding technique was used to remove the time-variable sky background and the thermal emission from the telescope. The chopping and nodding throws were  $15''$ , optimal for the galaxy size (minor axis  $\sim 2''$ ) and perpendicular to the semi-major axis of the galaxy<sup>1</sup>. The on-source integration times were 150 s for both galaxy images. Besides, images of a point spread function (PSF) standard star were obtained immediately after the science target in the N' and Qa filters for accurately sampling the image quality, and to allow flux calibration. We measured angular resolutions of  $0.32''$  and  $0.53''$  from the full width at half-maximum (FWHM) of these PSF standard stars. The fully reduced images of NGC 2992, taken from Ramos Almeida et al. (2009), are presented in Fig. 1. The N-band image shows a morphology consisting of a dominant point source and faint extended emission along  $PA \sim 30^\circ$ , whereas the Q-band image shows unresolved emission only. See Section 3.2 for more details.

In addition, a MIR spectrum covering the spectral range 8-13  $\mu\text{m}$  was obtained with the low resolution ( $R=\lambda/\Delta\lambda \sim 200$ ) MICHELLE N-band grating. A slit of  $\sim 0.4''$  width was used, oriented at  $PA = 0^\circ$ , and the on-source integration time was 1200 s. We used the reduced and flux calibrated spectrum from Colling (2011), also presented in Esquej et al. (2014).

#### 2.1.2 MIR Gran Telescopio CANARIAS/CanariCam observations

We obtained a N-band spectrum (7.5-13  $\mu\text{m}$ ) of NGC 2992, using the low spectral resolution ( $R \sim 175$ ) grating available in the instrument CanariCam (CC; Telesco et al. 2003), on the 10.4m GTC. CC is a MIR (7.5-25  $\mu\text{m}$ ) imager with spectroscopic, coronagraphic and polarimetric capabilities and uses a Si:As detector, which covers a FOV of  $26'' \times 19''$  on the sky and it has a pixel scale of  $0.0798''$  (hereafter  $0.08''$ ). The slit, of width  $\sim 0.52''$ , was oriented at  $PA = 30^\circ$ , following the faint extended emission revealed by the Gemini/MICHELLE imaging data (see Fig. 1). The total on-source integration time was 943 s and the standard MIR chopping-nodding technique was used, with chop and nod throws of  $15''$ .

The data were taken as part of an ESO/GTC large programme (182.B-2005; PI: Alonso-Herrero), aimed to conduct a MIR survey of nearby AGN by exploiting the unique capabilities of CC on the GTC (see Alonso-Herrero et al. 2013, 2014 for further details). The data reduction was carried out with the *RedCan* pipeline (González-Martín et al. 2013), which performs sky subtraction, stacking of individual observations, rejection of bad frames, wavelength calibration, trace determination and spectral extraction. We extracted a nuclear spectrum as a point source, and another spectrum as an extended source in an aperture radius of  $5.2''$  ( $\sim 905$  pc), which we then use to characterize the extended emission (see Section 3.1.2). Note that in the case of point source extraction, *RedCan* uses an aperture that increases with wavelength to take into account the decreasing angular resolution, and it also performs a correction to account for slit losses. For the extended source extraction, a fixed  $5.2''$  aperture and no slit-loss corrections were applied (see González-Martín et al. 2013 for further details on CC data reduction).

#### 2.1.3 Optical and NIR HST observations

We downloaded the fully reduced optical and NIR imaging data of NGC 2992 from the ESA Hubble Legacy Archive<sup>2</sup>. The optical image, shown in the left panel of Fig. 2, was observed with the F606W filter ( $\lambda_c=5975 \text{ \AA}$ ) using the Wide Field Planetary Camera 2 (WFPC2), which has a FOV of  $2.7' \times 2.7'$  on the sky and a pixel scale of  $0.046''$ . The NIR image (see right panel of Fig. 2) was observed with the F205W filter ( $\lambda_c=2.07 \mu\text{m}$ ) using the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), which has a FOV of  $19.2'' \times 19.2''$  on the sky and a pixel scale of  $0.075''$  (NIC2 camera). The downloaded NICMOS and WFPC2 images were reduced using the *NICRED* package (McLeod 1997) and the Space Telescope Science Analysis System (*STSDAS*) within *IRAF*<sup>3</sup>.

The optical and NIR data were taken as part of the Hubble programs P5479 (cycle:4, PI: M. Malkan) and P7869 (cycle:7, PI: A. Quillen), respectively. We refer the reader

<sup>1</sup> The chopping throw was chosen according to the galaxy size in the Gemini/MICHELLE image. We note that both the resolution and sensitivity of the Spitzer Space Telescope and Gemini are completely different, and thus, the large-scale IR emission that we detect in the Spitzer images is completely absent in the ground-based image and it does not affect the latter.

<sup>2</sup> <http://archives.esac.esa.int/hst/>

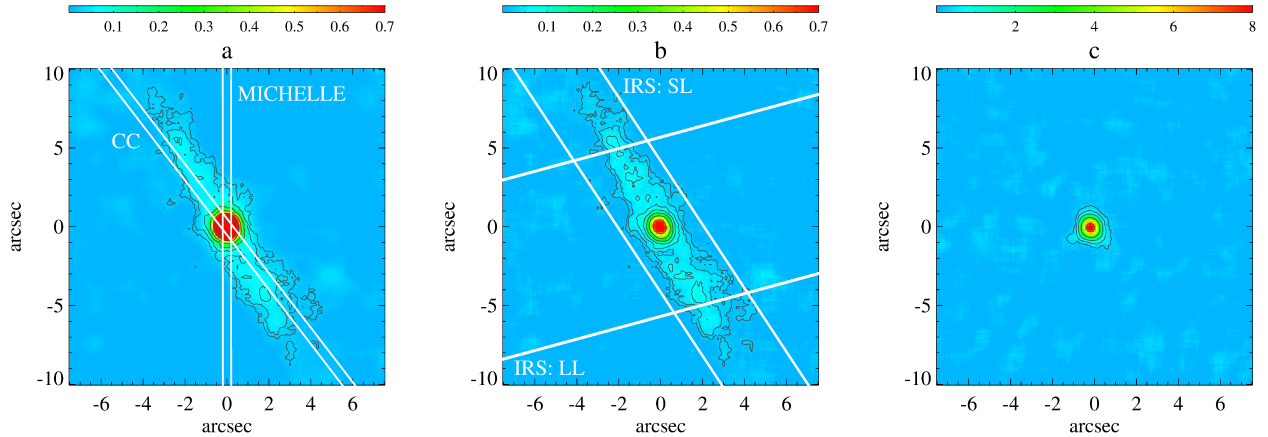
<sup>3</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

Wavelength $\lambda_c/\Delta\lambda$ ( $\mu\text{m}$ )	Imaging Filter/ Band	Telescope/Instrument Imaging	Spatial resolution (arcsec) (pc)	Pixel scale (arcsec/pixel)	Standard deviation $\sigma$ ( $10^{-2}$ )	Date (UT)
0.6/0.15	F606W	HST/WFPC2	0.095 17	0.046	1.3	1994 Oct 18
2.07/0.6	F205W	HST/NICMOS2	0.107 19	0.075	12.9	1998 Oct 15
3.6/0.75	Ch1	SPITZER/IRAC	1.85 322	0.6	0.01	2004 Dec 21
4.5/1.02	Ch2	SPITZER/IRAC	1.77 308	0.6	0.01	2004 Dec 21
5.8/1.43	Ch3	SPITZER/IRAC	2.15 374	0.6	0.08	2004 Dec 21
8/2.91	Ch4	SPITZER/IRAC	2.79 485	0.6	0.05	2004 Dec 21
11.2/2.4	N'	GEMINI/MICHELLE	0.32 56	0.1005	7.6	2006 May 12
18.1/1.9	Qa	GEMINI/MICHELLE	0.53 92	0.1005	68.4	2006 May 12
24/4.7	Ch1	SPITZER/MIPS	6.06 1054	1.225	0.2	2008 Jun 23
70/10.6	Blue	HERSCHEL/PACS	5.25 914	1.4	8.9	2011 May 16
100/17	Green	HERSCHEL/PACS	6.75 1175	1.7	12.3	2011 May 16
160/30.2	Red	HERSCHEL/PACS	10.80 1879	2.85	13.1	2011 May 16
250/75.76	PSW	HERSCHEL/SPIRE	17.63 3068	6	48.3	2010 Jun 21
350/102.94	PMW	HERSCHEL/SPIRE	24.49 4261	10	94.3	2010 Jun 21
500/200	PLW	HERSCHEL/SPIRE	34.66 6031	14	52.4	2010 Jun 21

Wavelength ( $\mu\text{m}$ )	Spectroscopy Slit width (arcsec)	Telescope/Instrument Spectroscopy	Spectral resolution $\lambda/\Delta\lambda$	Pixel scale (arcsec/pixel)	Exposure time (s)	Date (UT)
7.5-13	0.52	GTC/CANARICAM	$\sim 175$	0.0798	943	2014 Feb 13
8-13	0.4	GEMINI/MICHELLE	$\sim 200$	0.183	1200	2007 Mar 25
5.2-14.5	3.6-3.7	SPITZER/IRS SL	60-127	1.8	14	2005 Dec 10
14-38	10.5-10.7	SPITZER/IRS LL	57-126	5.1	6	2005 Dec 10

**Table 1.** Summary of the imaging and spectroscopic observations. The  $\sigma$  corresponds to the standard deviation of the sky background in mJy/pixel units. Note that the PACS observations were done using the normal/cross scan pattern, whereas the small map SPIRE observations were done using the nominal/cross scan pattern.



**Figure 1.** Gemini/MICHELLE images of NGC 2992. (a) MICHELLE 11.2  $\mu\text{m}$  image with the CanariCam and MICHELLE slits overlaid. (b) PSF-subtracted MICHELLE 11.2  $\mu\text{m}$  image with the Spitzer/IRS slits overlaid (see Section 2.2.1). (c) MICHELLE 18.1  $\mu\text{m}$  image. All images are smoothed (box of 6 pixels) and have their own contours overlaid (in black). Colour bars correspond to fluxes in mJy units. North is up, and east to the left.

to Malkan, Gorjian, & Tam (1998) and Quillen et al. (1999) for further details on these HST observations.

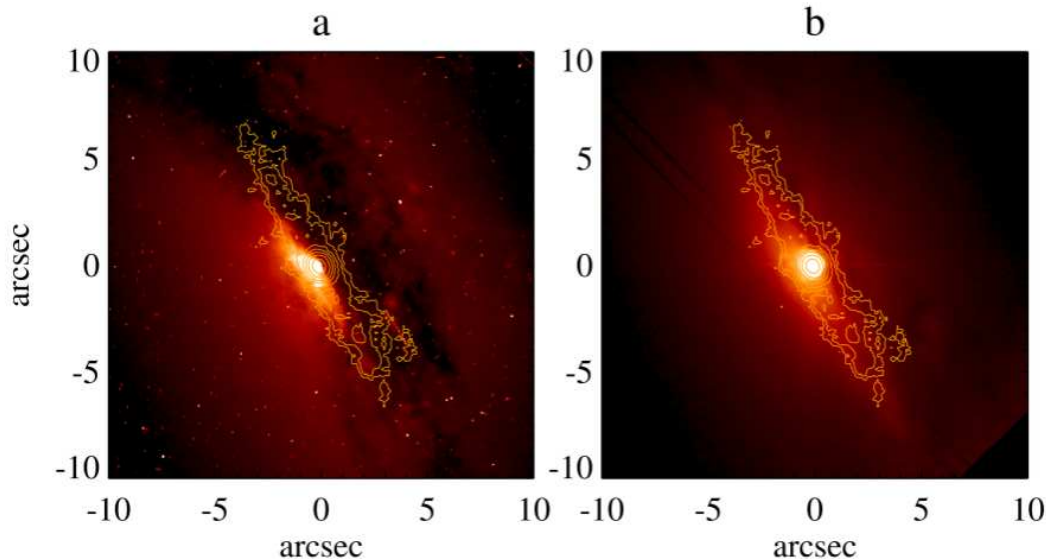
## 2.2 Arcsecond resolution data

### 2.2.1 MIR Spitzer Space Telescope observations

We downloaded imaging data of the Arp 245 system from the Spitzer Heritage Archive (SHA), taken with the instruments Infrared Array Camera (IRAC; Fazio et al. 2004) and Multi-

band Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). The IRAC FOV is  $5.2' \times 5.2'$  on the sky and its pixel scale is  $1.2''$ , whereas the MIPS FOV is  $5.4' \times 5.4'$  on the sky and its pixel scale is  $2.45''$ .

In addition, a low resolution MIR spectrum of NGC 2992 was retrieved from the Cornell Atlas of Spitzer/IRS Source (CASSIS v4; Lebouteiller et al. 2011). The spectrum was obtained using the InfraRed Spectrograph (IRS; Houck et al. 2004). The observation was made in staring mode using the two low-resolution ( $R \sim 60$ -120)



**Figure 2.** HST/WFPC2 optical image of NGC 2992 in the F606W filter (left panel), and HST/NICMOS NIR image in the F205W filter (right panel). Orange contours correspond to the PSF-subtracted Gemini/MICHELLE 11.2  $\mu\text{m}$  image (panel b in Fig. 1). North is up, and east to the left.

IRS modules: the short-low (SL; 5.2–14.5  $\mu\text{m}$ ) and the long-low (LL; 14–38  $\mu\text{m}$ ). The slits were oriented as shown in Fig. 1 and their widths are 3.6'' and 10.5'' for the SL and LL modules respectively.

The IRAC imaging data (3.6, 4.5, 5.8 and 8.0  $\mu\text{m}$ ) and the IRS spectrum were taken as part of the Spitzer program P96 (PI: J. R. Houck), and the MIPS imaging data (24  $\mu\text{m}$ ) under program P40936 (PI: G. Rieke). In the case of the IRAC images, we just downloaded the mosaicked data from the Spitzer archive, which have a pixel scale of 0.6''. On the other hand, the MIPS image was reprocessed using the MOsaicking and Point source EXtraction (*MOPEX*) software. Background gradients were removed by self-calibrating the data (see Section 8.1 of the MIPS Instrument Handbook 2011 for details) and the resulting mosaics were resampled to a pixel size of 1.225''.

We downloaded the IRS spectrum from the CASSIS database. The spectrum was reduced with the CASSIS software, using the optimal extraction to get the best signal-to-noise ratio. We only needed to apply a small offset to stitch together the different modules, taking the shorter wavelength module (SL2; 5.2–7.6  $\mu\text{m}$ ) as the basis, which has associated a slit width of 3.6'' ( $\sim 630$  pc). The IRS spectrum is shown in left panel of Fig. 3 (black dashed line) and it was also presented in Esquej et al. (2014).

### 2.2.2 FIR Herschel Space Observatory observations

FIR imaging data of the Arp 245 system were obtained with the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) and the Spectral and Photo-

metric Imaging REceiver (SPIRE; Griffin et al. 2010) on-board of the Herschel Space Observatory (Pilbratt et al. 2010). The data are part of the guaranteed time proposal “Herschel imaging photometry of nearby Seyferts galaxies: Testing the coexistence of AGN and SB activity and the nature of the dusty torus” (PI: M. Sánchez-Portal).

The PACS instrument has a FOV of  $1.75' \times 3.5'$  on the sky and three different bands (70, 100 and 160  $\mu\text{m}$ ), with beam sizes of 5.6, 6.8 and 11.3 arcsec FWHM, respectively. The PACS observations were carried out using the mini-map mode, consisting of two concatenated 3' scan line maps, at 70° and 110° (in array coordinates). This results in a map with a highly homogeneous exposure within the central 1' area. The SPIRE instrument has a FOV of  $4' \times 8'$  on the sky and three different bands (250, 350 and 500  $\mu\text{m}$ ), whose beam sizes are 18.1, 25.2 and 36.9 arcsec FWHM, respectively. These three available bands were observed simultaneously using the small map mode, whose area for scientific use is around  $5' \times 5'$ .

The PACS data processing was carried out by means of two tools: the Herschel Interactive Processing Environment (*HIPE*; Ott 2010) and *Scanamorphos* (Roussel 2012). In order to build the Level 1 products we used *HIPE* v8.0.1 with the PACS calibration database V32. This Level 1 processing included detecting and flagging bad pixels, converting the analogue to digital units readings to flux units (Jy/pixel) and adding the pointing information. We did not attempt to perform deglitching at this stage to prevent the bright AGN nucleus to be affected by the multi-resolution median transform deglitching process. The final maps were built from the Level 1 products using *Scanamorphos* v15, which performs

a baseline subtraction, correction of the striping effect due to the scan process, removal of global and individual pixel drifts, and finally the map assembly using all the nominal and cross-direction scans.

For the SPIRE data processing we built the Level 1 products with *HIPE* v8.0.1 and the SPIRE calibration database v8.1. The Level 1 processing included detection of thermistor jumps in the time line, frame deglitching, low-pass filter correction, conversion of readings to flux units (Jy/beam), temperature drift and bolometric time response corrections, and addition of pointing information. The final maps were built from the Level 1 using the Naïve Mapper functionality integrated in *HIPE* v8.0.1. This mapping strategy simply projects the integrated power seen by each bolometer onto the nearest sky map pixel. Once all the detector signals have been mapped, the flux density map and the standard deviations are calculated.

### 3 IR EMISSION OF THE SYSTEM

#### 3.1 Nuclear region of NGC 2992

In this section we study in detail the properties of the inner 100 pc of the galaxy NGC 2992 as well as the surrounding faint extended emission.

##### 3.1.1 Imaging

In Fig. 1 we show the high angular resolution MIR Gemini/MICHELLE images of NGC 2992. The  $11.2\ \mu\text{m}$  image reveals faint emission along  $\text{PA} \sim 30^\circ$  and extending out to  $\sim 3$  kpc (see more details in Section 3.2.1). This emission is coincident with the extended emission shown in the NIR HST image (right panel of Fig. 2). On the other hand, the optical HST image shows a thick dust lane that partly obscures the nucleus and whose orientation coincides with that of the extended emission ( $30^\circ$ ; left panel of Fig. 2). For the image registration, we first used the galaxy nucleus in the MICHELLE and NICMOS images, and then we used different stars in the FOV that the NICMOS and WFPC2 images have in common for centering the optical image. We note that the galaxy nucleus in the HST/NICMOS image is saturated. Finally, we measured a surface brightness of  $4.84 \pm 0.07$  mJy/arcsec<sup>2</sup> for the extended emission in the  $11.2\ \mu\text{m}$  image with the *PHOT* task of *IRAF*. We used an aperture of  $1''$  diameter in two different positions at both sides of the nucleus and we averaged the two measurements.

In addition to the extended emission seen in the  $11.2\ \mu\text{m}$  image there is an unresolved nuclear component, which is also present in the Q-band image. Ramos Almeida et al. (2009) estimated MIR nuclear fluxes of 175 and 521 mJy in the N- and Q-bands, respectively, by subtracting the PSF standard stars, observed in each filter before or after the science observations, from the galaxy profiles. In the central panel of Fig. 1 we show the PSF-subtracted N-band image of the galaxy, with the PSF scaled at 90%.

##### 3.1.2 Spectroscopy

In the left panel of Fig. 3 we show the GTC/CC and Gemini/MICHELLE 8-13  $\mu\text{m}$  nuclear spectra of NGC 2992, both

extracted as a point source. The GTC/CC spectrum has a spatial resolution of  $0.27''$  and the Gemini/MICHELLE spectrum of  $0.38''$ , which correspond to physical scales of  $\sim 47$  pc and  $\sim 66$  pc, respectively. Both angular resolutions were determined from the FWHM of the PSF star acquisition images.

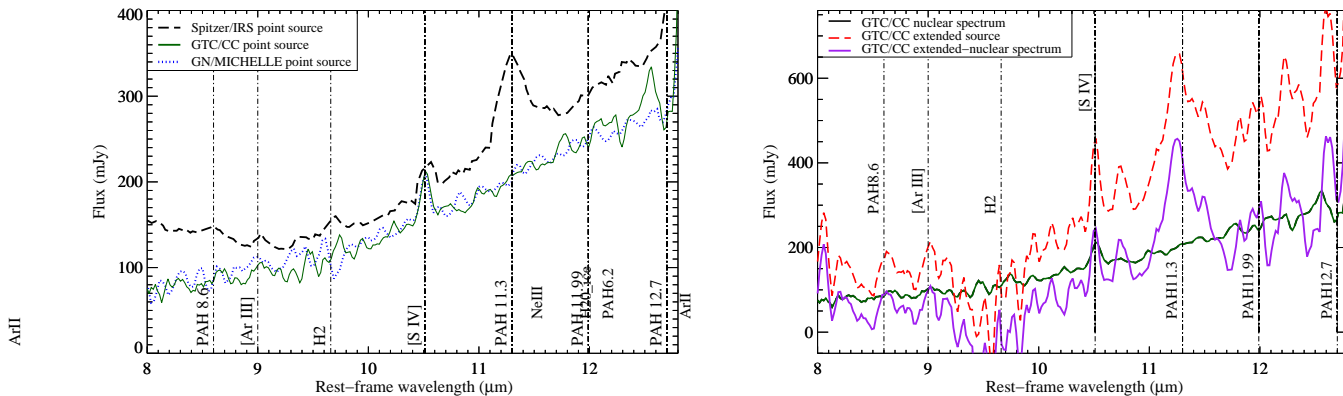
Despite the different slit orientations (see Fig. 1) and the time difference between the observations ( $\sim 7$  years), both spectra are practically identical. In spite of the IR variability reported by Glass (1997), we do not see any difference either in flux or shape. These spectra do not show PAH features and they exhibit [S IV] $\lambda 10.5\ \mu\text{m}$  emission, which can originate in the Narrow-Line Region (NLR) and it is usually considered an AGN tracer (Dasyra et al. 2011). However, this emission line can also be produced in star forming regions, as shown by Pereira-Santaella et al. (2010), due to its relatively low ionization potential (35 eV). For comparison, in the left panel of Fig. 3 we show the Spitzer/IRS spectrum in the same spectral range as the GTC/CC and Gemini/MICHELLE spectra, which has a spatial resolution of  $3.6''$ , that corresponds to a physical scale of  $\sim 630$  pc. Unlike the nuclear spectra, the IRS spectrum shows 8.6 and  $11.3\ \mu\text{m}$  PAH bands, indicative of the presence of SF on the scales probed by Spitzer.

In the right panel of Fig. 3 we show the nuclear GTC/CC spectrum, extracted as an extended source in an aperture radius of  $5.2''$  ( $\sim 905$  pc), the GTC/CC nuclear spectrum extracted as point source and the spectrum of the extended emission. The latter was obtained by subtracting the nuclear spectrum from the one extracted in the large aperture, in order to get rid of the AGN contribution. We chose this large aperture to increase the signal-to-noise of the extended emission spectrum. The spectra of the extended emission, before and after subtracting the AGN contribution, clearly show  $11.3\ \mu\text{m}$  PAH feature and the [S IV] $\lambda 10.5\ \mu\text{m}$  emission line, exactly as the Spitzer/IRS spectrum on scales of  $\sim 630$  pc. Thus, the faint extended emission that we detect in the Gemini/MICHELLE N-band image of the galaxy is, at least in part, due to SF. On the other hand, if we compare these spectra with the GTC/CC and Gemini/MICHELLE nuclear spectra shown in the left panel of Fig. 3, we can conclude that either the PAH features have been destroyed in the inner  $\sim 50$  pc of NGC 2992, or are diluted by the strong AGN continuum (see Alonso-Herrero et al. 2014 and Ramos Almeida et al. 2014).

##### 3.1.3 Nuclear SED modelling with clumpy torus models

Recent studies assumed a clumpy distribution of dust surrounding AGN to explain the properties of the nuclear IR SED of Seyfert galaxies (Mason et al. 2006, 2009; Nikutta, Elitzur, & Lacy 2009; Ramos Almeida et al. 2009, 2011a,b, 2014; Hönig & Kishimoto 2010; Alonso-Herrero et al. 2011, 2012a, 2013; Lira et al. 2013). Here we used the Nenkova et al. (2008a,b) clumpy torus models, commonly known as CLUMPY, and the Bayesian tool *BayesClumpy* (Asensio Ramos & Ramos Almeida 2009, 2013) to fit the nuclear IR emission of NGC 2992. The CLUMPY models are defined by six parameters (see Table 2), in addition to the foreground extinction and the vertical shift required to match the model to the observed SED. A detailed description of the Bayesian





**Figure 3.** Left panel: Spitzer/IRS rest-frame spectrum ( $\sim 630$  pc) of NGC 2992 (dashed black line) and GTC/CC and Gemini/MICHELLE rest-frame nuclear spectra ( $\sim 47$  and  $\sim 66$  pc) of NGC 2992 (solid green and dotted blue lines respectively), extracted as a point source. Right panel: GTC/CC spectrum of NGC 2992 extracted as an extended source in an aperture radius of  $5.2'' \sim 905$  pc (dashed red line), GTC/CC nuclear spectrum (as in left panel; solid green line) and spectrum of the extended emission (solid purple line), obtained by subtracting the nuclear spectrum from the one extracted in the  $5.2''$  aperture radius. In both panels, the vertical dotted lines indicate the position of typical star-forming regions/AGN emission lines/bands. All spectra have been smoothed (2 pixel box).

inference applied to the CLUMPY models can be found in Asensio Ramos & Ramos Almeida (2009).

We constructed the nuclear IR SED of NGC 2992 using the GTC/CC spectrum, which is more recent and has better angular resolution than the Gemini/MICHELLE one, extracted as a point source and re-sampled to 50 points; the UKIRT NIR nuclear fluxes from Alonso-Herrero et al. (2001); the MICHELLE MIR fluxes from Ramos Almeida et al. (2009); and the  $30 \mu\text{m}$  flux from the Spitzer/IRS spectrum (see Fig. 4). There is good agreement between the flux calibration of the nuclear spectrum and the nuclear  $11.2 \mu\text{m}$  flux, as we only measured a 10% mismatch between them. For consistency, we scaled the spectrum to the nuclear  $11.2 \mu\text{m}$  flux and we estimated a 15% total uncertainty for the GTC/CC spectrum by quadratically adding the errors in the flux calibration and point source extraction. We used the NIR nuclear photometry as upper limits because of the lower angular resolution of the UKIRT data. We did not use the HST/NICMOS image available in the archive for obtaining a NIR nuclear flux because the galaxy nucleus is saturated. We finally considered the IRS  $30 \mu\text{m}$  flux as an upper limit, due to the low angular resolution of Spitzer.

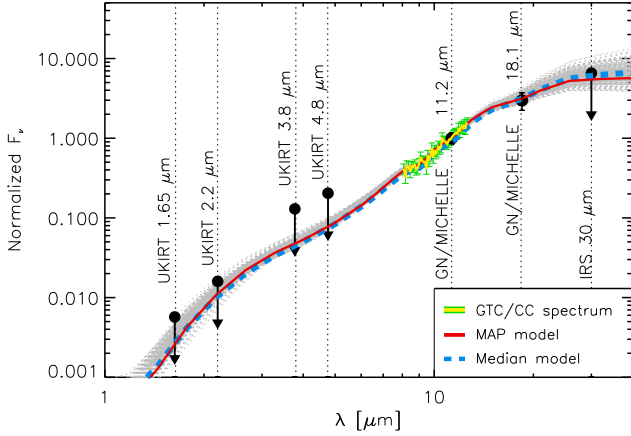
We fitted the SED of NGC 2992 considering reprocessed torus emission and foreground extinction, using the IR extinction curve of Chiar & Tielens (2006). We used the prior  $A_V^{(for)} = [2, 5]$  mag in our fit, taking into account the extinction value of  $A_V \sim 4$  mag reported by Chapman et al. (2000) for the innermost region of the galaxy. The opening angle of the ionization cones is  $130^\circ$ , as measured from the [O III] image reported by García-Lorenzo, Arribas, & Mediavilla (2001). This would correspond to a torus width of  $25^\circ$  and therefore we used the prior  $\sigma = [15^\circ, 35^\circ]$  in our fit. We also used the prior  $i = [45^\circ, 65^\circ]$  for the inclination angle of the torus, based on the values reported for the orientation of the accretion disk by Gilli et al. (2000) using X-ray data, and from modelling of the kinematics of the NLR presented in Müller-Sánchez et al. (2011). The result of the fitting pro-

Parameter	Prior	Median	MAP
$\sigma$	$[15^\circ, 35^\circ]$	$34^\circ \pm 1^\circ$	$35^\circ$
$Y$	$[5, 100]$	$16 \pm 3$	12
$N_0$	$[1, 15]$	$14 \pm 1$	15
$q$	$[0, 3]$	$0.6 \pm 0.3$	0.5
$i$	$[45^\circ, 65^\circ]$	$64^\circ \pm 1^\circ$	$65^\circ$
$\tau_V$	$[5, 150]$	$105 \pm 15$	109
$A_V^{(for)}$	$[2, 5]$ mag	$4.1 \pm 0.9$ mag	5.0 mag
$R_o$	...	$1.4 \pm 0.5$ pc	1.2 pc
$L_{bol}^{AGN}/10^{43}$	...	$5.9 \pm 1.2$ erg s $^{-1}$	$5.8$ erg s $^{-1}$
$M_{torus}/10^5$	...	$1.3 \pm 0.3 M_\odot$	$0.9 M_\odot$
$N_H/10^{24}$	...	$1.7 \pm 0.2$ cm $^{-2}$	$3.4$ cm $^{-2}$

**Table 2.** Clumpy model parameters, intervals considered as uniform priors, median and MAP values of the posteriors resulting from the fit of NGC 2992 nuclear SED. ( $\sigma$ : width of clouds angular distribution;  $Y$ : radial extent of the torus;  $N_0$ : clouds along equatorial ray;  $q$ : index of the radial density profile;  $i$ : inclination angle of the torus (Note:  $i=0^\circ$  is face-on and  $i=90^\circ$  is edge-on);  $\tau_V$ : optical depth per single cloud;  $A_V^{(for)}$ : foreground extinction). The last 4 rows correspond to the torus outer radius, the AGN bolometric luminosity, the torus gas mass and the hydrogen column density derived from the fit.

cess are the posterior distributions of the parameters, but we can also translate the results into a best-fitting model, described by the combination of parameters that maximizes the posterior (maximum-a-posteriori; MAP) and a median model, computed with the median value of each posterior (see Fig. 4). The MAP and median parameters of NGC 2992 are shown in Table 2.

From the fit presented in Fig. 4 we find that we require a foreground extinction, unrelated to the torus, of  $A_V^{(for)} \sim 5$  mag in the case of the MAP model. This is in good agreement with the value derived from the fit of the silicate feature reported by Colling (2011) using the Gemini/MICHELLE nuclear spectrum of NGC 2992 ( $\tau_{9.7\mu\text{m}} \sim 0.3$ ).



**Figure 4.** Nuclear IR SED of NGC 2992 normalized at 11.2  $\mu\text{m}$  (thick yellow line: GTC/CC nuclear spectrum; black dots: UKIRT NIR fluxes from Alonso-Herrero et al. (2001) and Gemini/MICHELLE 11.2, 18.1  $\mu\text{m}$  fluxes from Ramos Almeida et al. (2009) and 30  $\mu\text{m}$  flux from the Spitzer/IRS spectrum). Solid red and dashed blue lines correspond to the MAP and median models respectively. Grey curves are the clumpy models sampled from the posterior and compatible with the data at  $1\sigma$  level.

We derived a small torus radius from the MAP torus model, of 1.2 pc, in agreement with the results from interferometry of nearby Seyfert galaxies (see Burtcher et al. 2013 and references therein). The torus covering factor is  $\sim 0.5$ , which is more similar to the values reported by Ramos Almeida et al. (2011a) for Seyfert 1 galaxies, and which could explain the variations in Seyfert type of NGC 2992 (See Section 6.1 for a discussion). We derived the AGN bolometric luminosity from the vertical shift applied to the MAP model to fit the data (see Ramos Almeida et al. 2011a and Alonso-Herrero et al. 2011 for further details), and we obtained  $L_{\text{bol}}^{\text{AGN}} = 5.8 \times 10^{43} \text{ erg s}^{-1}$ . This is consistent with the most recent X-ray observations available in the literature ( $L_{\text{bol}}^{\text{X-ray}} = 3.2 \times 10^{43} \text{ erg s}^{-1}$ ; see Table 3), taken in 2005. Using the MAP value of the total optical extinction produced by the torus ( $A_V^{\text{torus}} = 1776 \text{ mag}$ ) we can derive the column density using the dust-to-gas ratio  $N_H^{\text{LOS}} = 1.9 \times 10^{21} \times A_V^{\text{torus}}$  (Bohlin, Savage, & Drake 1978). This gives  $N_H = 3.4 \times 10^{24} \text{ cm}^{-2}$ , which is within the range reported by Weaver et al. (1996) for the cold dense gas detected in the inner  $\sim 3$  pc of the galaxy in the X-rays ( $\sim 10^{23} - 10^{25} \text{ cm}^{-2}$ ). We also estimated the torus gas mass using equation 4 in Nenkova et al. (2008b), which is a function of the parameters  $\sigma$ ,  $N_0$ ,  $\tau_V$ ,  $Y$  and the sublimation radius of the torus. We obtain a torus gas mass of  $M_{\text{torus}} = 9 \times 10^4 M_\odot$ , which is of the same order as that measured by García-Burillo et al. (2014) for the central 20 pc of the Seyfert 2 NGC 1068 using cycle 0 data from the Atacama Large Millimeter/submillimeter Array (ALMA;  $M_{\text{gas}} = 1.2 \times 10^5 M_\odot$ ). The good agreement between  $L_{\text{bol}}^{\text{X-ray}}$  and  $L_{\text{bol}}^{\text{AGN}}$ , in addition to the good match between the models and the IR observations, confirm that the clumpy torus fitted here provides a realistic scenario for the inner parsecs of NGC 2992.

$L_{\text{bol}}^{\text{X-ray}}$ ( $\text{erg s}^{-1}$ )	Date	Telescope	Reference
$2.3 \times 10^{44}$	1978	HEAO 1	Mushotzky (1982)
$8.9 \times 10^{43}$	1979	Einstein	Turner et al. (1991)
$2.5 \times 10^{43}$	1990	Ginga	Nandra & Pounds (1994)
$1.4 \times 10^{43}$	1994	ASCA	Weaver et al. (1996)
$1.2 \times 10^{43}$	1997	BeppoSAX 1	Gilli et al. (2000)
$1.4 \times 10^{44}$	1998	BeppoSAX 2	Gilli et al. (2000)
$2.6 \times 10^{44}$	2003	XMM-Newton	Shu et al. (2010)
$2.5 \times 10^{44}$	2003	XMM-Newton	Brightman & Nandra (2011)
$3.2 \times 10^{43}$	2005	Suzaku	Yaqoob et al. (2007)

**Table 3.** NGC 2992 bolometric luminosities obtained from the 2-10 keV X-ray intrinsic luminosities (by multiplying by a factor 20 as in Elvis et al. 1994). For the non-intrinsic X-ray luminosity values, a factor 70 has been used in addition to the bolometric correction factor, as in Marinucci et al. (2012).

### 3.2 Large scale emission

In this section we study the large scale IR morphology of the interacting system Arp 245 (see Fig. 5), which consists of three galaxies undergoing strong tidal interaction: the spirals NGC 2992 and NGC 2993 and the tidal dwarf galaxy Arp 245N. There is a fourth galaxy that is also part of the system: FGC 0938, but it lies outside the Spitzer and Herschel FOVs.

#### 3.2.1 NGC 2992

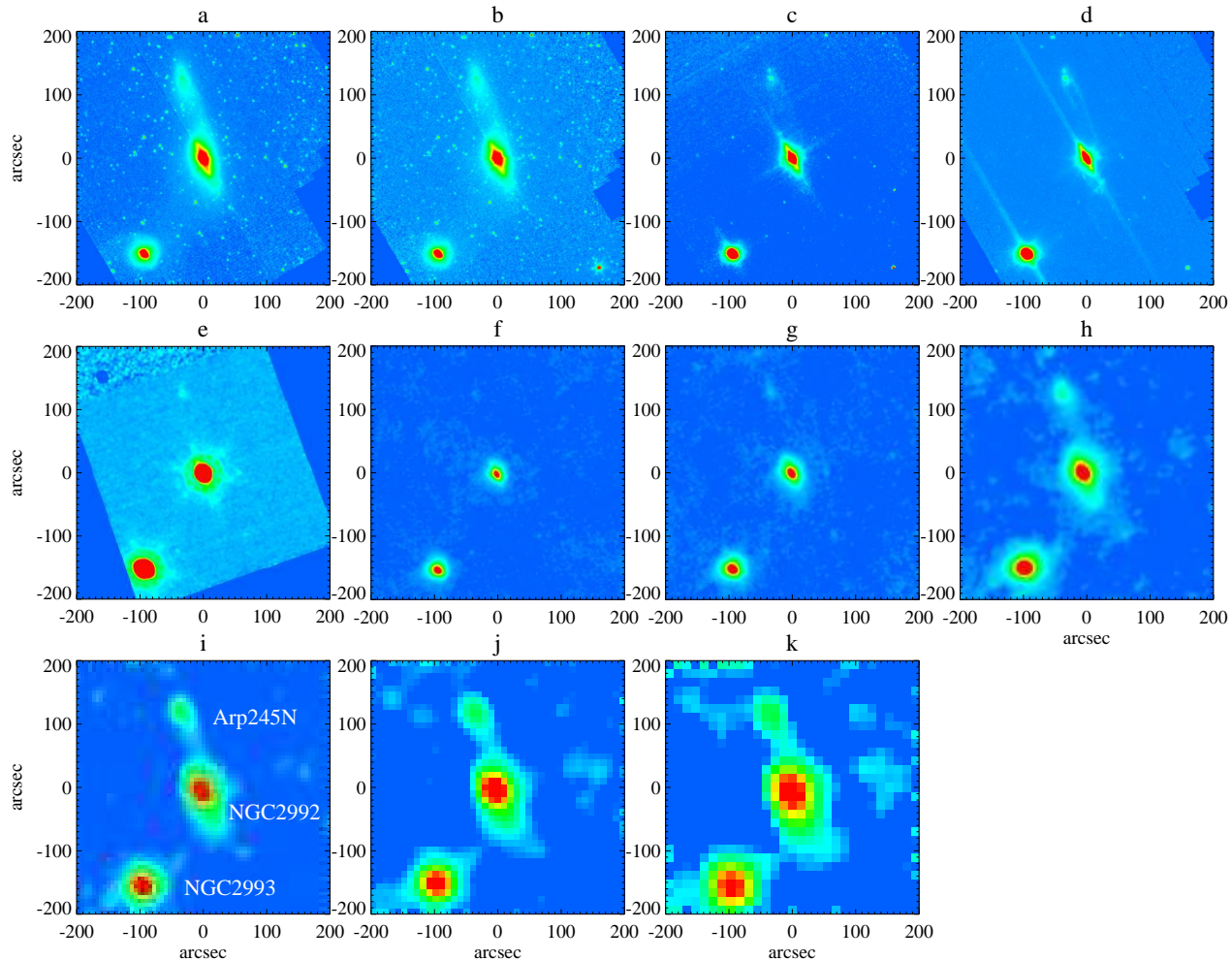
In Fig. 6 we show Spitzer/IRAC & MIPS and Herschel/PACS & SPIRE images of NGC 2992 in a  $120'' \times 120''$  FOV. The extended emission in the IRAC images is elongated in the same direction as the faint extended emission detected in the Gemini/MICHELLE N-band and HST/NICMOS images (see Fig. 2), and it also coincides with the orientation of the galaxy major axis. Considering that the spectrum of the extended emission shows a strong 11.3  $\mu\text{m}$  PAH feature (see Section 3.1.2), the bulk of this faint emission is likely produced by dust heated by star formation. In the case of the IRAC images the source of the IR emission depends on the band we look at, with the 3.6 and 4.5  $\mu\text{m}$  emission likely dominated by starlight and the 5.8 and 8  $\mu\text{m}$  emission by dust heated by star formation and the AGN (e.g. Draine et al. 2007).

The MIPS 24  $\mu\text{m}$  image, on the other hand, is rather point-like, as the Gemini/MICHELLE Q-band emission seen in the right panel of Fig. 1. The 70 and 100  $\mu\text{m}$  emission seen in the Herschel/PACS images (panels f and g in Fig. 6) is barely resolved and slightly elongated in the same direction as the Spitzer/IRAC images. From 160 to 500  $\mu\text{m}$ , the intensity of the extended emission increases significantly, produced by cooler dust in the galaxy (panels h-k in Fig. 6).

#### 3.2.2 Arp 245 system

In Fig. 5 we show Spitzer/IRAC & MIPS and Herschel/PACS & SPIRE images of the interacting system Arp 245. NGC 2992 and Arp 245N show clearly distorted morphologies, and they are linked by a tidal tail which appears very bright in the Spitzer/IRAC images. The bridge





**Figure 5.** Spitzer and Herschel images of the Arp 245 system. NGC 2992 is the central galaxy, NGC 2993 is at the bottom left corner of the images, and Arp 245N is at the top. The four IRAC channels (3.6, 4.5, 5.8 and 8  $\mu\text{m}$ ) are shown in panels a-d, the MIPS channel 1 image (24  $\mu\text{m}$ ) in panel e, the PACS 70, 100 and 160  $\mu\text{m}$  images in panels f-h, and the SPIRE 250, 350 and 500  $\mu\text{m}$  images in panels i-k. All images have been smoothed (3 pixels box). North is up, and east to left.

(Arp 245 Bridge) between NGC 2992 and NGC 2993 is more conspicuous in the Herschel/SPIRE maps, indicating the presence of cooler dust.

We measured total galaxy fluxes for the three galaxies to construct their IR SEDs, which are shown in Fig. 7 and Table 4. We used a large aperture (60'' radius for NGC 2992/93 and 25'' radius for Arp 245N) to collect all the galaxy flux<sup>4</sup>, and subtracted the sky background. The IR SEDs of NGC 2992/93 shown in Fig. 7 also include NIR total fluxes from 2MASS, reported by Jarrett et al. (2003).

As can be seen from Fig. 7, the total SEDs of NGC 2992 and NGC 2993 are very similar at wavelengths longer than 8  $\mu\text{m}$ . This similarity is likely related to the presence of intense SF in both galaxies, which heats the dust at similar temperatures. This is corroborated by the SED fitting pre-

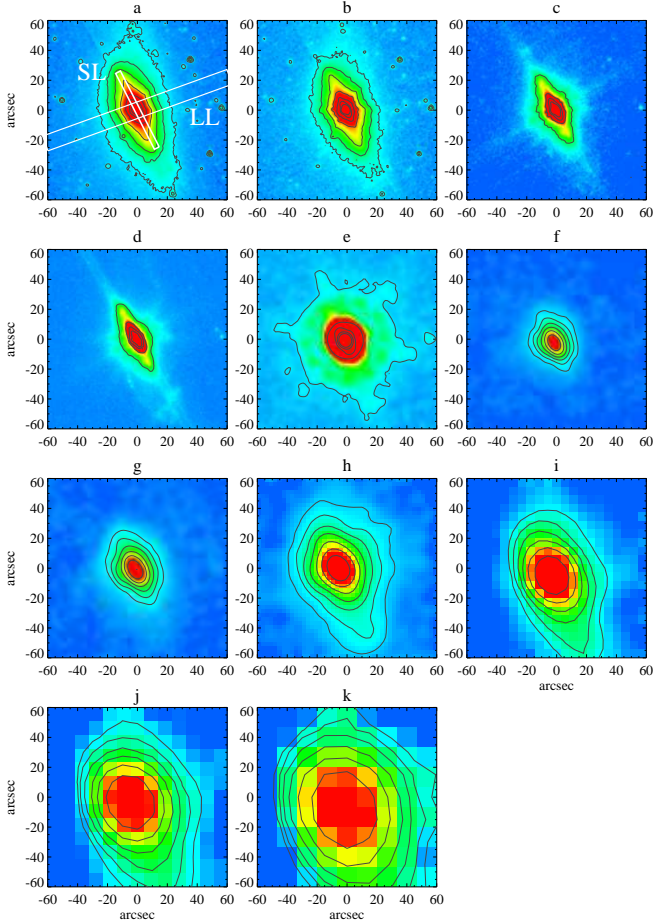
sented in Section 5. On the other hand, the total SEDs are different in flux level at shorter wavelengths ( $\lambda < 8 \mu\text{m}$ ), with NGC 2992 being brighter. Considering that the 3.6 and 4.5  $\mu\text{m}$  emission is dominated by the Rayleigh-Jeans tail of stellar photospheric emission (Howell et al. 2007), the brighter NIR SED of NGC 2992 is likely due to its larger stellar mass, as compared to that of NGC 2993 (Duc et al. 2000), and, to a lesser extent, to the extra-contribution from dust heated by the AGN. Nevertheless, we note that the SED shapes at these shorter wavelengths are very similar, and characteristic of old stellar populations.

The fainter SED of Arp 245N has a similar shape to those of NGC 2992 and NGC 2993 SEDs, except in the  $\sim 24$ -100  $\mu\text{m}$  range, where the fluxes are lower compared to other wavelengths. This can be indicative of a relatively weak illuminating radiation field that may possibly be consistent with weak SF activity (see Section 5). We refer the reader to Draine & Li (2007) and Dale et al. (2014) for further discussion.

<sup>4</sup> In the case of the MIPS 24  $\mu\text{m}$  image, we used an aperture radius of 25'' to calculate the total flux of NGC 2993, which is too close to the image edge.

	3.6 $\mu$ m	4.5 $\mu$ m	5.8 $\mu$ m	8 $\mu$ m	24 $\mu$ m	70 $\mu$ m	100 $\mu$ m	160 $\mu$ m	250 $\mu$ m	350 $\mu$ m	500 $\mu$ m
NGC 2992	180 $\pm$ 19	158 $\pm$ 19	244 $\pm$ 25	510 $\pm$ 53	1000 $\pm$ 108	9070 $\pm$ 1014	12018 $\pm$ 1344	10794 $\pm$ 1207	3882 $\pm$ 443	2104 $\pm$ 240	357 $\pm$ 41
NGC 2993	55 $\pm$ 6	41 $\pm$ 4	132 $\pm$ 14	527 $\pm$ 60	1182 $\pm$ 127	12138 $\pm$ 1357	13880 $\pm$ 1552	10776 $\pm$ 1205	3291 $\pm$ 376	1714 $\pm$ 196	291 $\pm$ 33
Arp 245N	7 $\pm$ 1	4 $\pm$ 1	8 $\pm$ 1	22 $\pm$ 2	3 $\pm$ 1	77 $\pm$ 9	163 $\pm$ 18	394 $\pm$ 44	279 $\pm$ 32	176 $\pm$ 20	31 $\pm$ 4

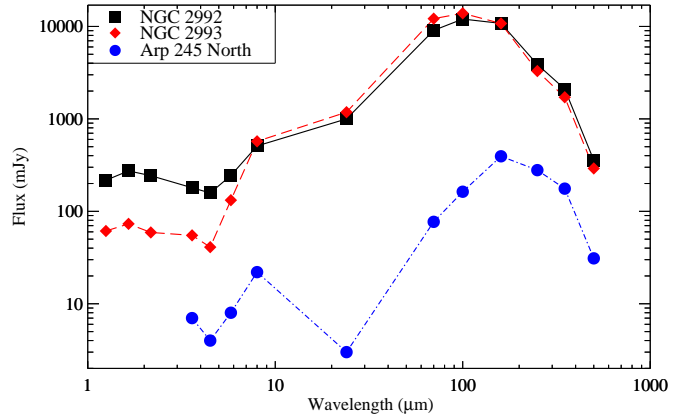
**Table 4.** Total fluxes measured for NGC 2992, NGC 2993 and Arp 245N in mJy. The flux errors are the result of adding quadratically the calibration uncertainties [3% for IRAC (IRAC Instrument Handbook 2013), 4% for MIPS at 24  $\mu$ m (MIPS Instrument Handbook 2011), 5% for PACS (PACS Observer’s Manual 2013) and 5.5% for SPIRE (SPIRE Handbook 2014)] and the estimated uncertainty for aperture photometry ( $\sim$ 10%). Note that in the case of SPIRE, extended sources have an additional 4% error due to uncertainty in the measurement of the beam area.



**Figure 6.** Same as in Fig. 5, but for NGC 2992. Panel (a) shows the orientation of the Spitzer/IRS slits. All images have been smoothed (3 pixels box) and have their own contours overlaid (in black).

#### 4 RECOVERING NUCLEAR INFORMATION FROM ARCSECOND RESOLUTION DATA

In this section we used different methods to try to recover the nuclear emission of NGC 2992 from the lower angular resolution data of Spitzer and Herschel. This kind of analysis is important due to the paucity of ground-based MIR instruments and to the difficulty of observing in the MIR range from ground. In this case, we have the opportunity to compare with the nuclear fluxes obtained from the high angular



**Figure 7.** NGC 2992, NGC 2993 and Arp 245N total IR SEDs (black solid, red dashed and blue dot-dashed lines respectively).

resolution data presented here, obtained using GTC/CC and Gemini/MICHELLE.

##### 4.1 Recovering the nuclear IR SED

In order to try to recover the nuclear IR SED of NGC 2992 from low angular resolution data, we used two different methods, which are described below.

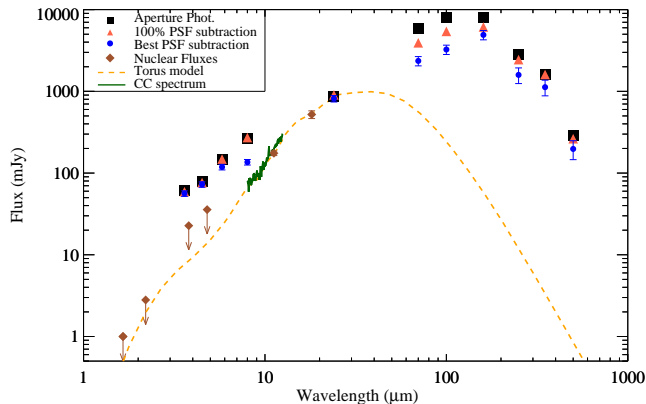
###### 4.1.1 Aperture Photometry

We used aperture photometry of the galaxy nucleus in the Spitzer and Herschel images. The photometry was carried out with the *DIGIPHOT* package of *IRAF*. We used different apertures (multiples of the FWHM in each band; see Table 5) and the sky subtraction was carried out using a concentric ring large enough to exclude the galaxy emission. We finally applied corresponding aperture corrections in order to recover the unresolved galaxy flux. These correction factors were computed from the extended Point Response Functions (PRFs) for IRAC<sup>5</sup>, the core PRF for MIPS<sup>2</sup> and synthetic PSFs for Herschel/ PACS<sup>6</sup> and SPIRE<sup>7</sup>. We performed aperture photometry on the PRFs and PSFs stars, using the same apertures as for the galaxy in each band,

<sup>5</sup> <http://irsa.ipac.caltech.edu/data/SPITZER/docs/>

<sup>6</sup> <ftp://ftp.sciops.esa.int/pub/hsc-calibration/PACS/PSF/>

<sup>7</sup> <ftp://ftp.sciops.esa.int/pub/hsc-calibration/SPIRE/PHOT/>



**Figure 8.** Nuclear fluxes of NGC 2992 from low angular resolution data calculated using aperture photometry (squares) and PSF subtraction at various levels (triangles and circles). The nuclear IR SED (diamonds), including the GTC/CC spectrum and the torus model fitted in Section 3.1.3, are shown for comparison.

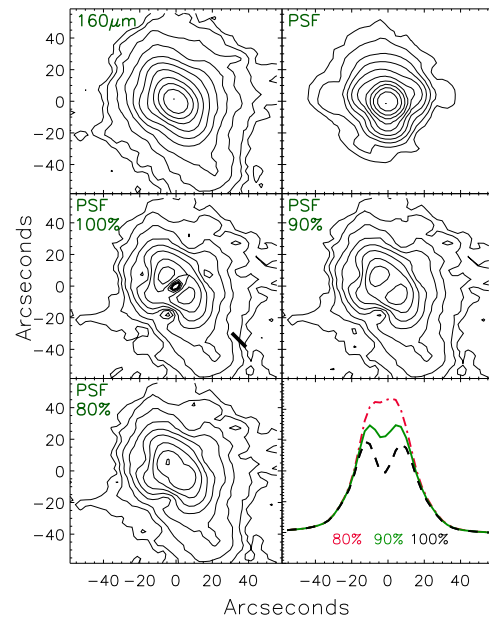
and calculated the different correction factors by comparing each individual value with the total flux, measured in an aperture large enough to contain all the star flux. Note that the synthetic PSFs have different pixel scales than the science data and we used the *MAGNIFY* task of *IRAF* to resample the PSF images.

We took multiples of the FWHM and then we applied aperture corrections for each one. We find that the aperture corrections converged around 2 FWHM, and then chose this aperture to estimate the nuclear fluxes. In Table 5 and Fig. 8 we show the nuclear galaxy fluxes calculated using this method and including aperture corrections.

#### 4.1.2 Subtraction of scaled PSFs

As the aperture photometry might include contamination from the foreground galaxy, here we use the PRF and PSF stars to obtain more realistic nuclear fluxes. First, we scaled the PSF stars to the peak of the galaxy emission in each band, which represents the maximum contribution of the unresolved source, and we integrated the flux in an aperture large enough to contain all the star flux. Then, the host galaxy contribution corresponds to the total galaxy emission minus the scaled PSF (i.e. the residual of the subtraction). We require a relatively flat profile in the residual for a realistic galaxy profile and therefore reduce the scale of the PSF from matching the peak of the galaxy emission to obtain the unresolved fluxes, as in Radomski et al. (2002) and Ramos Almeida et al. (2009). Fig. 9 shows an example of PSF subtraction at various levels (in  $3\sigma$  contours) for the  $160\ \mu\text{m}$  Herschel/PACS image. In this case 80% PSF subtraction produces a flatter profile than 90 and 100%, which are clearly over-subtracted.

The nuclear fluxes calculated using this method are shown in Table 5 and Fig. 8. We also included the results from 100% PSF subtraction, which are more similar to the aperture photometry fluxes, calculated in Section 4.1.1. We note that the relatively flat profile required to determine the best PSF subtraction level might not be com-



**Figure 9.**  $160\ \mu\text{m}$  Herschel/PACS contours of NGC 2992, the PSF star and the scaled PSF subtraction at the 80, 90 and 100% levels (red dot-dashed, solid green and black dashed lines respectively). The best subtraction is 80%, according to the flat galaxy profile shown in the bottom-right panel. North is up, and east to left.

pletely flat due to possible diffuse or irregular dust structures (Muñoz-Mateos et al. 2009). This potential issue could be affecting the fluxes calculated using this method.

In Fig. 8 we compare the high angular resolution SED and the MAP torus model (see Fig. 4) with those from aperture photometry and PSF subtraction. The latter includes 100% and best PSF subtraction, where the percentage of the best PSF subtraction corresponds to the one that produces the flattest galaxy profile in each band. The best PSF subtraction fluxes are the smallest, but still significantly larger than the high angular resolution SED. Therefore, we find that we cannot recover the nuclear SED from the Spitzer and Herschel data, with the exception of the  $24\ \mu\text{m}$  flux, which we recover with both methods. This is expected, since at  $20\text{--}25\ \mu\text{m}$  the torus emission is supposed to dominate (see Ramos Almeida et al. 2011a and references therein). At shorter and longer wavelengths the galaxy contribution increases and contaminates our aperture photometry and PSF subtracted fluxes.

## 4.2 Spectral Decomposition

Considering the spatial scales probed by the Spitzer/IRS spectrum of NGC 2992 ( $\sim 630\ \text{pc}$ ) and the prominent  $11.3\ \mu\text{m}$  PAH feature shown in Fig. 3, we expect contributions from the AGN and SF on these scales. To estimate the AGN contribution to the Spitzer/IRS spectrum, we take the simple approach of decomposing it in AGN and SB components. To do that, we used the average spectrum of local SB of Brandl et al. (2006) and the templates of purely star-forming LIRGs of Rieke et al. (2009), which cover the IR

Instrument/ Band	Wavelength $\lambda_c$ ( $\mu\text{m}$ )	FWHM (arcsec)	FWHM (pc)	Aperture photometry flux	Flux uncertainty (percent)	100% PSF subtraction flux	Best PSF subtraction (percent)	flux	Flux uncertainty (percent)
IRAC/Ch1	3.6	1.85	322	61	10	59	95	56	15
IRAC/Ch2	4.5	1.77	308	78	10	76	95	73	15
IRAC/Ch3	5.8	2.15	374	148	10	148	80	119	15
IRAC/Ch4	8.0	2.79	485	261	10	272	50	136	15
MIPS/Ch1	24	6.13	1067	874	11	905	90	815	16
PACS/Blue	70	5.25	914	5852	11	3929	60	2357	16
PACS/Green	100	6.75	1175	8080	11	5417	60	3250	16
PACS/Red	160	10.80	1879	7910	11	6135	80	4908	16
SPIRE/PSW	250	17.63	3068	2805	11	2446	65	1590	16
SPIRE/PMW	350	24.49	4261	1608	11	1607	70	1125	16
SPIRE/PLW	500	34.66	6031	287	11	263	75	197	16

**Table 5.** NGC 2992 nuclear fluxes calculated using aperture photometry and PSF subtraction (all fluxes in mJy units). Column 1 and 2 list the instrument/band and its central wavelength ( $\mu\text{m}$ ). Column 3 and 4 correspond to each band resolution in arcsec and parsecs. Columns 5 and 6 list the aperture photometry fluxes and corresponding errors, with the aperture photometry carried out in an aperture equals to 2 FWHM (See Section 4.1.1). Column 7 corresponds to the fluxes obtained from 100% PSF subtraction, and columns 8, 9 and 10 list the best percentage of PSF subtraction used in each band, corresponding fluxes and errors. The flux errors are the result of adding quadratically the flux calibration uncertainties (see Table 4) and the errors associated with either aperture photometry ( $\sim 10\%$ ) or PSF subtraction ( $\sim 15\%$ ).

luminosity range  $10 \leq \log(L_{\text{IR}}/L_{\odot}) \leq 12$ . As AGN template we used the MAP clumpy torus model (i.e. the best-fitting model) fitted in Section 3.1.3, and shown in Fig. 4. The fitting procedure is described in detail in Alonso-Herrero et al. (2012b).

The fit was carried out in the spectral range 6–30  $\mu\text{m}$  to avoid the slightly decreased signal-to-noise of the longest wavelengths. We tried different combinations of AGN + SB templates, allowing rescaling of the two components. We finally chose the fit that minimized the  $\chi^2$ , which in this case was the SB template of IR luminosity  $\log(L_{\text{IR}}/L_{\odot})=10$  of Rieke et al. (2009), in combination with the AGN. This IR luminosity is indeed similar to that of NGC 2992 ( $\log(L_{\text{IR}}/L_{\odot}) = 10.52$ ; Sanders et al. 2003). The result of the fit is shown in the top panel of Fig. 10. We have quantified the AGN fractional contributions to the total 6, 20 and 30  $\mu\text{m}$  emission and obtained 34, 88 and 81% respectively. We note that the scaled AGN template coincides with the nuclear GTC/CC spectrum within the errors, proving the reliability of the method employed here.

By using this method we are taking advantage of the privileged information of the high angular resolution GTC/CC spectrum. Therefore, we repeated the same process without using this information and we tried to recover the AGN and SF contributions using the average Seyfert 2 CLUMPY torus model fit reported by Ramos Almeida et al. (2011a) as initial AGN template. In this case the fitted AGN component does not match the high angular resolution GTC/CC spectrum and therefore it is necessary to perform an iterative process to obtain a reliable fit. After the first fit, we subtracted the SB template from the Spitzer/IRS spectrum, and then fitted the residual with BayesClumpy. We then performed a second fit using the latter MAP model and the SB templates and repeated the process until the solution converged. To quantify that, we used the AGN fractional contributions at the wavelengths listed before. The percentages at 20 and 30  $\mu\text{m}$  converged after the fourth iteration, but at 6  $\mu\text{m}$  convergence is not reached. This is due to the

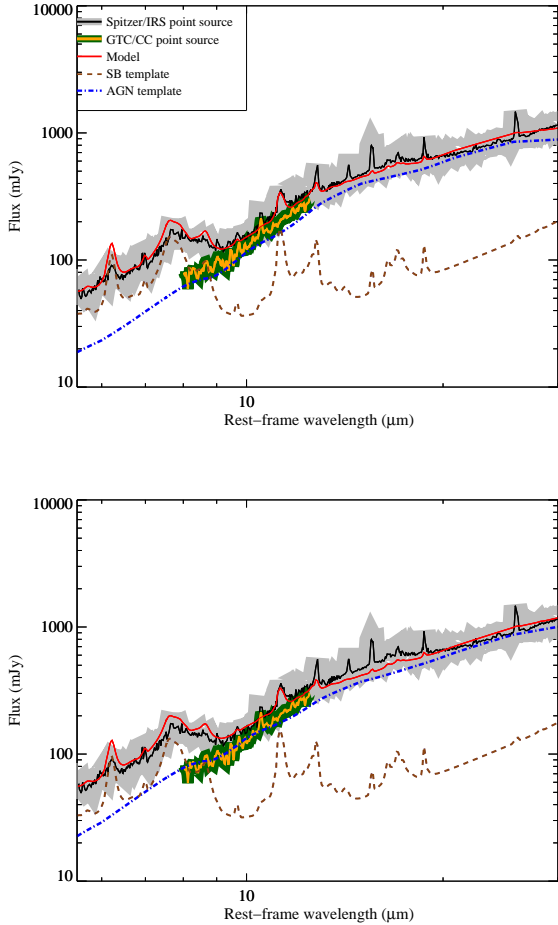
prominent PAH features at 6.2, 7.7 and 8.6  $\mu\text{m}$  of the SB template, which results in a overestimation of the PAHs contribution to the Spitzer/IRS spectrum at these wavelengths. The result of this iterative process is shown in the bottom panel of Fig. 10. The AGN fractional contributions to the total 6, 20 and 30  $\mu\text{m}$  emission are 43, 88 and 85% respectively. Therefore, we recover the AGN spectrum of NGC 2992 using only the generic torus models from Ramos Almeida et al. (2011a), and we obtain practically identical AGN fractional contributions at 20 and 30  $\mu\text{m}$  using the two methods described here.

The contribution from SF to the Spitzer/IRS spectrum of NGC 2992 is concentrated on the PAH features at 6.2, 7.7, 8.6 and 11.3  $\mu\text{m}$ , as shown in Fig. 10. At shorter wavelengths ( $\lambda \lesssim 15 \mu\text{m}$ ) the SB component is stronger than the AGN component, with a  $\sim 60$ – $70\%$  contribution at 6  $\mu\text{m}$ . However, at longer wavelengths ( $\lambda \gtrsim 15 \mu\text{m}$ ) the AGN becomes dominant, reaching  $\sim 90\%$  at 20–25  $\mu\text{m}$ . At  $\lambda > 25 \mu\text{m}$ , the AGN contribution slowly decreases (see also next section), in agreement with the results reported by Mullaney et al. (2011) for a sample of intermediate luminosity AGN ( $L_{2-10\text{keV}} \sim 10^{42-44} \text{ erg s}^{-1}$ ), whose 6–100  $\mu\text{m}$  SEDs are best described by a broken power-law that generally peaks between 15–20  $\mu\text{m}$ , and finally falls strongly at  $\lambda \gtrsim 40 \mu\text{m}$ .

## 5 PHYSICAL PARAMETERS OF THE CIRCUMNUCLEAR DUST EMISSION OF THE SYSTEM

Dust grains in Seyfert galaxies are heated mainly by SF and nuclear activity, and this radiation is reemitted in the IR range. The physical properties of large dust grains can be accurately described by a single modified blackbody (Bianchi 2013), and this dust component, heated by the interstellar radiation field, would contain the bulk of the dust mass in a galaxy (Dale et al. 2012). On the other hand, the physical properties of smaller dust grains, i.e. those producing

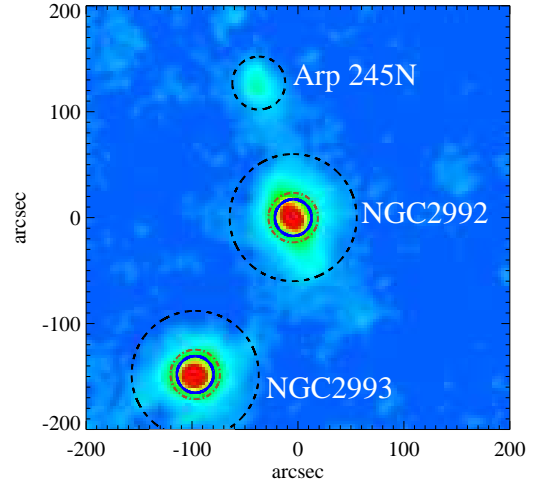




**Figure 10.** NGC 2992 6–30  $\mu\text{m}$  Spitzer/IRS rest-frame spectrum (black solid line), best fit (red solid line), MAP torus model (blue dot-dashed line), and SB template (brown dashed line). Top panel: Fit using the MAP torus model fitted to the high angular resolution IR SED of NGC 2992. Bottom panel: Fit using the average Seyfert 2 torus model fit from Ramos Almeida et al. (2011a) and applying an iterative process. The 8–13  $\mu\text{m}$  GTC/CC rest-frame spectrum is shown in both panels for comparison (smoothed with a 2 pixel box; orange line). The uncertainties of the Spitzer/IRS and GTC/CC spectra are shown as grey and dark green shaded regions respectively.

warmer components, are better described by a blend of multiple modified blackbodies with different temperatures (Draine & Li 2007).

For the sake of simplicity, here we will consider single components to describe the shape of the FIR SEDs of NGC 2992 and NGC 2993. This is a similar approach to that used by Pérez García & Rodríguez Espinosa (2001) and Prieto & Acosta-Pulido (2003) to reproduce the IR SED of Seyfert galaxies as the sum of three components: 1) a warm dust component, produced by dust heated by SF and/or nuclear activity at  $T \sim 120\text{--}170$  K; 2) a cold component ( $T \sim 30\text{--}70$  K), associated with SF regions; and 3) a very cold component ( $T \sim 15\text{--}25$  K), produced by dust heated by the interstellar radiation field. The warm component peaks in the MIR range, and both the cold and very cold dust components are detected in the FIR range.



**Figure 11.** Schema of the different apertures used to calculate the circumnuclear and disk emission of NGC 2992/93, and the total flux of Arp 245N. The apertures are overplotted on the 160  $\mu\text{m}$  Herschel/PACS image of the system. Blue solid and brown dot-dashed circles correspond to the apertures used to calculate the fluxes of the circumnuclear component and the galaxy background that we subtract from the former to get rid of the underlying disk emission. Black dashed circles correspond to the apertures used to calculate the total galaxy fluxes reported in Table 4. The disk emission is calculated by subtracting the circumnuclear fluxes from the total emission.

In the case of the galaxies NGC 2992/93, we consider two different regions to separate the circumnuclear emission from the diffuse and more extended disk emission, as we did in Ramos Almeida et al. (2011c) for the Seyfert 2 galaxy NGC 3081. The circumnuclear region is delimited by a circular aperture of  $\sim 35''$  diameter ( $\sim 6$  kpc), coincident with the largest FWHM of the Herschel data (i.e. SPIRE 500  $\mu\text{m}$ ; blue solid circles in Fig. 11). We first extracted Herschel/PACS and SPIRE fluxes within such aperture and then subtracted the corresponding galaxy background measured in an adjacent annulus (brown dot-dashed circles in Fig. 11). In the case of the active galaxy NGC 2992 we also subtracted the torus model emission (described in Section 3.1.3), which is the main contributor to the warm dust component in this galaxy. The circumnuclear fluxes are represented as red squares in Fig. 12 and reported in Table 6.

The disk emission is computed as the difference between the total fluxes reported in Table 4 (calculated in apertures of 120'' diameter; black dashed circles in Fig. 11) minus the circumnuclear fluxes. These values are plotted as green circles in Fig. 12 and reported in Table 6.

In order to quantify the temperatures and dust masses of the two components described above we used the following relation:  $M_{\text{dust}} = D^2 f_\nu / \kappa_\nu B(T)$  (Hildebrand 1983; Bianchi 2013) to fit the FIR SEDs.  $D$  is the luminosity distance to the galaxy,  $f_\nu$  the flux density,  $\kappa_\nu$  the absorption opacity

	70 $\mu\text{m}$ (mJy)	100 $\mu\text{m}$ (mJy)	160 $\mu\text{m}$ (mJy)	250 $\mu\text{m}$ (mJy)	350 $\mu\text{m}$ (mJy)	500 $\mu\text{m}$ (mJy)	Temperature (K)	$M_{\text{dust}}$ ( $10^6 M_{\odot}$ )	SFR ( $M_{\odot}/\text{yr}$ )
NGC 2992 (a)	6801 $\pm$ 1075	9013 $\pm$ 1424	6759 $\pm$ 1068	2124 $\pm$ 363	570 $\pm$ 97	40 $\pm$ 7	29 $\pm$ 1	7.6 $\pm$ 1.3	2.5 $\pm$ 0.4
NGC 2992 (b)	1751 $\pm$ 277	2776 $\pm$ 439	3981 $\pm$ 629	1743 $\pm$ 298	1530 $\pm$ 262	316 $\pm$ 54	21 $\pm$ 1	19.6 $\pm$ 2.7	0.7 $\pm$ 0.1
NGC 2993 (a)	10083 $\pm$ 1593	10979 $\pm$ 1735	7153 $\pm$ 1130	1625 $\pm$ 278	488 $\pm$ 83	42 $\pm$ 7	33 $\pm$ 1	4.7 $\pm$ 0.8	3.7 $\pm$ 0.6
NGC 2993 (b)	2055 $\pm$ 325	2902 $\pm$ 459	3623 $\pm$ 572	1666 $\pm$ 285	1266 $\pm$ 216	249 $\pm$ 43	22 $\pm$ 1	14.9 $\pm$ 2.0	0.8 $\pm$ 0.1
Arp 245N	77 $\pm$ 9	163 $\pm$ 18	394 $\pm$ 44	279 $\pm$ 32	176 $\pm$ 20	31 $\pm$ 4	19 $\pm$ 1	3.2 $\pm$ 1.1	$\sim$ 0.03

**Table 6.** Fluxes of the circumnuclear (a) and disk (b) components of NGC 2992 and NGC 2993 described in Section 5, total fluxes of Arp 245N and physical properties derived from the SED fits shown in Fig. 12. See Fig. 11 for further details on the different apertures employed.

of the dust at frequency  $\nu^8$ , and  $B(T)$  the Planck function evaluated at temperature  $T$ .

The fits to the circumnuclear and disk FIR SEDs of NGC 2992/93 are shown in the top and central panels of Fig. 12<sup>9</sup>. The best fits correspond to dust temperatures of 29 $\pm$ 1 K and 33 $\pm$ 1 K respectively (see Table 6). These temperatures explain the similarity between the total MIR-to-FIR SEDs of the two spiral galaxies (see Fig. 7). On the other hand, the SEDs of the disks can be described by a dust component of 21 $\pm$ 1 K and 22 $\pm$ 1 K respectively (see Table 6). These temperatures coincide with the lowest values reported by Skibba et al. (2011) for the nearby galaxies in the KINGFISH Herschel survey ( $T \sim 20$ -35 K). They are also consistent with the values measured for the coldest dust components of Seyfert galaxies (e.g. Radovich et al. 1999; Ramos Almeida et al. 2011c; Bendo et al. 2010) using Herschel data as in this study.

The dust masses that we measure for the two components are reported in Table 6. We obtain similar values for the two spiral galaxies:  $\sim 5$ -8  $\times 10^6 M_{\odot}$  and  $\sim 15$ -20  $\times 10^6 M_{\odot}$  for the circumnuclear and galaxy disk components respectively, with those of NGC 2992 being slightly larger. These dust masses are within the lowest values reported by da Cunha et al. (2010) for a sample of star-forming galaxies, using the  $M_{\text{dust}}$ -star formation rate (SFR) relation ( $M_d \sim 10$ -100  $\times 10^6 M_{\odot}$  for the galaxies with the highest S/N of the sample).

We also measured total fluxes for the dwarf galaxy Arp 245N in an aperture radius of 25'', after subtracting the sky background (see Table 6 and Fig. 11)<sup>10</sup>. These fluxes are plotted as brown triangles in the bottom panel of Fig. 12, and fitted using a temperature of 19 $\pm$ 1 K and a total dust mass of  $M_{\text{dust}} = (3.2 \pm 1.1) \times 10^6 M_{\odot}$ . This low temperature is compatible with dust heated by the interstellar radiation field and the relatively weak MIR emission of the galaxy in the range  $\sim 24$ -100  $\mu\text{m}$  (see Fig. 7) would be indicating that a significant part of the old stellar population and the interstellar medium of NGC 2992 and NGC 2993 have been

stripped from the galaxies during the interaction process undergone by the system.

Finally, we estimated SFRs for the three galaxies in the system using the 70  $\mu\text{m}$  fluxes reported in Table 6 and equation 14 in Rieke et al. (2009). We decided to use the 70  $\mu\text{m}$  fluxes because the 24  $\mu\text{m}$  flux is dominated by the AGN contribution in the case of NGC 2992. However, we checked that we obtain similar SFR estimations for NGC 2993 and Arp 245N when using 24 and 100  $\mu\text{m}$  fluxes. The SFRs that we measure for the two spiral galaxies are very similar considering the errors (see Table 6). For Arp 245N we derive a small SFR ( $\sim 0.03 M_{\odot}/\text{yr}$ ), consistent with the low temperature of the dust and the weak MIR emission.

## 6 DISCUSSION

### 6.1 NGC 2992

NGC 2992 contains a Seyfert 1.9 nucleus, although it has changed its type between Seyfert 1.5 and 2 and it has also exhibited huge variations across all the spectrum (Trippe et al. 2008). The 2-10 keV X-ray luminosity dramatically decreased between 1978 and 1994 (a factor of  $\sim 16$ ; see Table 3) and then increased by roughly the same amount from 1994 to 2005 (Gilli et al. 2000; Yaqoob et al. 2007; Brightman & Nandra 2011). Besides, Glass (1997) reported variability in the NIR, with the source fading from 1978 to 1996, except for a strong outburst in 1988. This IR variability mirrors that detected in the X-ray regime, with the corresponding delay due to the different scales that each emission is probing (Clavel, Wamsteker, & Glass 1989; Barvainis 1992; Hönig & Kishimoto 2011). Gilli et al. (2000) explained the extreme variability of NGC 2992 as caused by a retriggered AGN, and in particular, by different stages of the rebuilding of the accretion disk, which the latter authors estimated to range between 1 and 5 years.

According to the new observations reported here, the nuclear MIR spectrum of NGC 2992 has not changed either in flux or shape from 2007 to 2014. This is in agreement with the scenario proposed by Gilli et al. (2000), in which the rebuilding of the accretion disk would have been finished in 2005, first stopping the X-ray variability and finally, the IR variability. Monitoring campaigns in the X-ray and the optical/IR are then key to constrain the relative sizes of the AGN internal structures as well as to understand the physics of nuclear activity.

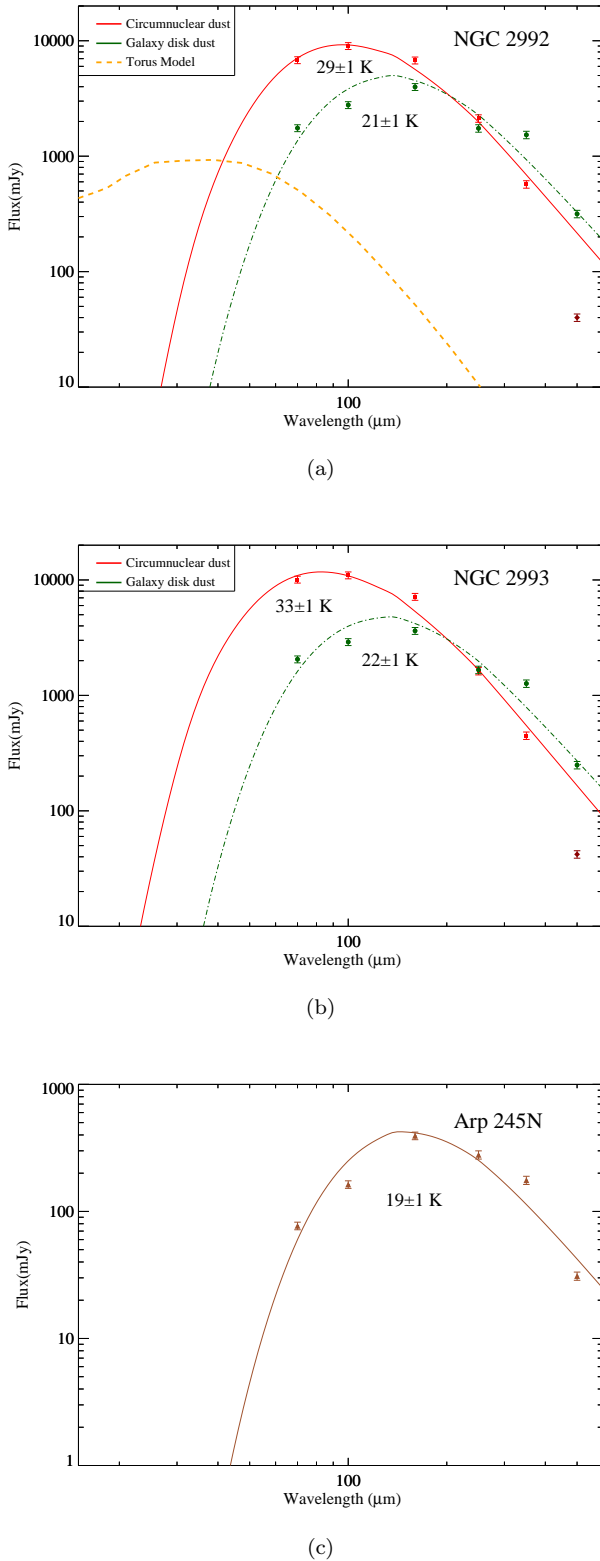
In Section 3.1.3 we derived a column density of  $N_H \sim 10^{24} \text{ cm}^{-2}$  from the fit of the nuclear SED with clumpy

<sup>8</sup> The average absorption cross section is available at <http://www.astro.princeton.edu/~draine/dust/dustmix.html>. In this paper we use the  $R_V = 3.1$  MW dust model. See Li & Draine (2001) for further details.

<sup>9</sup> Note that we excluded the circumnuclear SPIRE 500  $\mu\text{m}$  fluxes from the fits, as they are underestimated because the circumnuclear aperture does not include an important part of the unresolved flux in this band.

<sup>10</sup> These fluxes are same as those reported in Table 4.





**Figure 12.** Top and central panels: fits to the circumnuclear and disk SEDs of NGC 2992/93 (red solid and green dot-dashed lines respectively). The MAP torus model fitted in Section 3.1.3 is also shown in the case of NGC 2992 (orange dashed line). Bottom panel: SED fit of Arp 245N (solid brown line). Note that in the top and central panels we represent the circumnuclear SPIRE 500  $\mu\text{m}$  fluxes as dark red diamonds, which are excluded from the fits because they are clearly underestimated (see Section 5).

torus models. This column density is much higher than the values derived from X-ray measurements, as e.g. the  $N_H \sim 10^{22} \text{ cm}^{-2}$  reported by Gilli et al. (2000) or the  $N_H = 8 \times 10^{21} \text{ cm}^{-2}$  reported by Yaqoob et al. (2007). However, Weaver et al. (1996) measured a narrow and prominent Fe K $\alpha$  line with a large equivalent width ( $\sim 500 \text{ eV}$ ) from X-ray data taken with the Advanced Satellite for Cosmology and Astrophysics (ASCA). The strong Fe K $\alpha$  line and the Compton-reflection component inferred by Weaver et al. (1996) require the existence of cold dense gas with a column of density of  $N_H \sim 10^{23}\text{--}10^{25} \text{ cm}^{-2}$ , which comprises the value derived from our fit. Moreover, Weaver et al. (1996) associated the lag in the response of these X-ray features to changes in continuum flux, from which they estimated the reprocessor size to be  $\sim 3 \text{ pc}$ . This is roughly in agreement with the torus size derived from our fit ( $R_o = 1.5 \pm 0.5 \text{ pc}$ ). Therefore, a clumpy torus with the properties derived from the fit performed here is in agreement with the scenario proposed by Weaver et al. (1996). On the other hand, the intermediate covering factor of the torus that we infer from the fit presented in Section 3.1.3 could explain the changes in Seyfert type experienced by NGC 2992 (Trippe et al. 2008).

In Section 4.2 we used clumpy torus models and a set of SB templates to decompose the Spitzer/IRS spectrum of NGC 2992, which probes the central kpc of the galaxy. We found an important contribution from SF at short MIR wavelengths ( $\lambda \sim 6\text{--}15 \mu\text{m}$ ; 60–70%), which is concentrated on the PAH features at 6.2, 7.7, 8.6 and  $11.3 \mu\text{m}$ . On the other hand, at  $\lambda \sim 15\text{--}30 \mu\text{m}$ , the AGN dominates the Spitzer/IRS spectrum, reaching 90% at 20–25  $\mu\text{m}$ . A similar, but more simplistic approach was taken by Deo et al. (2009) using Spitzer/IRS data in mapping-mode<sup>11</sup>. They subtracted the average starburst galaxy spectrum from Brandl et al. (2006) from the Spitzer/IRS spectrum after scaling it, aiming to completely remove the 11.3 and 17  $\mu\text{m}$  PAH features from the residual. By using this method, they found that the contribution from the SB increases with wavelength, as opposed to what we find using our spectral decomposition technique. We also tried a fit using clumpy torus models and the Brandl et al. (2006) SB template, but the result did not successfully reproduce the Spitzer/IRS spectrum. In addition, from the analysis of the IR photometry performed in Section 4 we know that the AGN emission, in the scales probed by Spitzer, becomes dominant at 20–25  $\mu\text{m}$ , in agreement with the results derived from spectroscopic data. Finally, using the high angular resolution imaging and spectroscopic data of NGC 2992 presented here, we have shown that SF is either suppressed or diluted by the strong AGN radiation field in the inner  $\sim 50 \text{ pc}$  of the galaxy (See Section 3.1.2), as shown by the lack of PAH features in the nuclear spectrum.

## 6.2 The Arp 245 interacting system

As previously mentioned, the interacting system Arp 245 is formed by the two spiral galaxies NGC 2992/93, the dwarf galaxy Arp 245N and two major tidal features. These features consist on two bridges connecting the three galax-

<sup>11</sup> In this work we are using the Spitzer/IRS spectrum of NGC 2992 in staring-mode.

ies (see Fig. 5). The fact that the tidal features are well-developed indicates that the system is seen close after its first encounter (see Duc et al. 2000 and references therein). Furthermore, the northern bridge linking NGC 2992 and Arp 245N is relatively bright and dense, whereas that associated with NGC 2993 appears like a weaker large open ring. The prominence of the two bridges suggests that the two spiral galaxies are experiencing prograde encounters (galaxy spins in the same sense as the flyby; Toomre & Toomre 1972). Nonetheless, the bridges extend  $\sim 16$  and  $27$  kpc respectively, which are rather modest extents compared with the long 100 kpc antennae observed in the prototypical interacting galaxy pair NGC 4038/39. However, these lengths are expected for an interacting system in an early phase such as Arp 245, with the bridges still developing. This is confirmed by the numerical modeling performed by Duc et al. (2000), which predicts that the first galaxy encounter happened  $\sim 100$  Myr ago.

According to Tadhunter et al. (2011) and Ramos Almeida et al. (2011b), three main stages can be defined in a galaxy merger sequence: *i*) pre-coalescence, *ii*) coalescence, and *iii*) post-coalescence. In the pre-coalescence phase the two nuclei are observed after the first passage, and immediately before ( $\sim 100$  Myr) the coalescence of the two nuclei. The peak of AGN activity is expected during coalescence, although during the pre-coalescence most objects tend to also exhibit AGN or SB activity associated with the gas infall produced by the tidal forces at play. This is indeed the case of the galaxy pair NGC 2992/93: NGC 2992 is known to host a Seyfert nucleus, and all the galaxies show circumnuclear SF, as revealed by their FIR luminosities (see Section 3.2) and the H $\alpha$  imaging presented in Duc et al. (2000).

A more recent study on interacting systems is presented in Lanz et al. (2013), where the authors measured and modelled the galaxy SEDs from the ultraviolet to the FIR, also using Spitzer and Herschel data to cover the IR range. From this modelling they derived temperatures, dust masses and SFRs for the galaxies in their sample. In addition, Lanz et al. (2013) classify the galaxies in different interaction stages attending to the galaxy morphologies, using a similar classification scheme as in Dopita et al. (2002). They divide the sample in four categories: 1) non-interacting galaxies; 2) galaxies in a weak integrating system, which are close but show minimal morphological distortion; 3) moderately interacting galaxies showing strong signs of morphological disturbance such as tidal tails; and 4) strongly interacting galaxies in a more evolved stage of the interaction.

As explained above, the Arp 245 system would be in the pre-coalescence stage of the interaction, which would correspond to stages 3/4 of the classification employed by Lanz et al. (2013). For these stages they report average dust masses of  $\sim 1\text{--}4 \times 10^7 M_\odot$ , dust temperatures of  $\sim 20\text{--}23$  K, and SFRs of  $\sim 0.6\text{--}7.8 M_\odot/\text{yr}$ . These values are consistent with the measurements reported in Table 6 for the disk components of NGC 2992/93, being more similar to the stage 3 values, i.e., moderately integrating galaxies showing strong signs of morphological disturbance.

Using the determined dust masses for the spiral galax-

ies, we derived gas-to-dust ratios<sup>12</sup> of 70 and 50 for NGC 2992 and NGC 2993 respectively. These ratios are comparable to those measured in other nearby galaxies, including active and non-active galaxies. As an example, see the results obtained for the Spitzer IR Nearby Galaxies Survey (SINGS; Draine et al. 2007).

A remarkable feature is the similarity of the MIR-to-FIR (beyond  $10 \mu\text{m}$ ) emission coming from the two spiral galaxies (see Figure 7). They are closely matched in luminosity and spectral shape. We can compare the SFRs derived from our FIR data with those obtained by Duc et al. (2000) from H $\alpha$  imaging. As expected, the largest contribution to the SFR comes from the circumnuclear region (ratio 4.5:1 relative to the disk). Adding the two contributions we obtain  $3.2$  and  $4.5 M_\odot \text{ yr}^{-1}$  for NGC 2992 and NGC 2993, respectively. Duc et al. (2000) reported H $\alpha$  luminosities of  $1.7$  and  $2.8 \times 10^{41} \text{ erg s}^{-1}$  for the two spirals, which can be transformed to SFRs, resulting in  $0.7$  and  $1.14 M_\odot \text{ yr}^{-1}$  for NGC 2992 and NGC 2993 respectively. We corrected these figures for extinction using  $E(B-V)=0.84$  and  $0.7$  for NGC 2992/93, measured from the recombination lines (Durret & Bergeron 1988). The extinction-corrected values are  $9.1$  and  $9.8 M_\odot \text{ yr}^{-1}$  for NGC 2992 and NGC 2993 respectively, which are larger than the values that we derive here. However, we note that the average extinction correction that we are using may not be adequate, since the integrated H $\alpha$  emission comes from regions with different levels of obscuration.

All the tidal features observed in the optical images of the Arp 245 system (Duc et al. 2000) have counterparts in the MIR-to-FIR observations presented here (see Fig. 5), although they show different properties. The galaxy Arp 245N, that is clearly detected in the four Spitzer/IRAC bands (from  $3.6$  to  $8 \mu\text{m}$ ), becomes much fainter at  $24$  and  $70 \mu\text{m}$ , and arises again at wavelengths beyond  $100 \mu\text{m}$ . This bimodal emission fits with the hypothesis made by Duc et al. (2000), who proposed this source to be formed by an old stellar population tidally stripped from NGC 2992, plus a minor contribution from young stars formed in-situ after the interaction. The latter is spectroscopically corroborated by the presence of H $\alpha$  and H $\beta$  emission. The EW of H $\beta$  emission line indicates that the SB started less than  $10$  Myr ago (Duc et al. 2000). Using the PACS  $70 \mu\text{m}$  flux of Arp 245N, we derived a relatively low SFR per unit area ( $\Sigma\text{SFR}$ ):  $\text{Log } \Sigma\text{SFR} \sim -3.3 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ , which is considerably larger than the extinction-corrected value reported by Duc et al. (2000), of  $-2.5 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ , obtained from the H $\alpha$  luminosity. This difference could be due to an overestimation of the extinction correction applied by Duc et al. (2000), who measured  $\text{Log } \Sigma\text{SFR} \sim -3.1 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$  before correcting for extinction. The gas-to-dust mass ratio that we measured for Arp 245N is  $\sim 280$ , which might indicate that this region is a HI reservoir, where the dust content is relatively low, as well as the SF.

The Arp 245 Bridge is only detected at wavelengths longer than  $160 \mu\text{m}$  (see Fig. 5), indicating the presence

<sup>12</sup> The HI mass has been taken from Duc et al. (2000). We note that we calculate the gas-to-dust ratios using atomic gas masses, but it is possible that a substantial fraction of the gas mass is in molecular form.

of very cold dust. There is no evidence for dust heated by SF activity in this feature, which is corroborated by the lack of ionized gas in the  $H\alpha$  images (Duc et al. 2000). The lack of recent SF in the bridge would indicate that the conditions are not adequate, i.e., the HI column density could be below the threshold required for SF to take place.

Summarizing, the MIR-to-FIR maps presented in this work are in good agreement with the system being in an early phase of the interaction between the galaxy pair NGC 2992/93 ( $\sim 100$  Myr after the first encounter). The MIR-to-FIR luminosities indicate that both spirals are relatively bright IR galaxies, with the SF activity mostly concentrated in the circumnuclear regions. On the other hand, the tidal features have not reached the conditions to be active star forming sites.

IR studies of interacting systems are important to advance in our understanding of the evolution of the gas/dust properties of such systems as the interaction evolves. Our work contributes to this understanding with the analysis of two spiral galaxies in clear interaction, one of them an AGN, and a dwarf galaxy likely stripped from NGC 2992. The different dust properties of the dwarf galaxy and the two spirals provide one more piece of information about how star formation and nuclear activity are triggered in galaxy interactions, but similar studies of other interacting systems in different stages of the interaction, including galaxies of different masses and types, are fundamental to derive general conclusions.

## 7 CONCLUSIONS

We have presented Spitzer and Herschel IR imaging of the interacting system Arp 245, and high angular resolution IR imaging and MIR spectroscopic observations of the Seyfert 1.9 galaxy NGC 2992. For NGC 2992, we have used different methods to recover the nuclear emission from the Spitzer and Herschel data, and compared it with the ground-based IR observations of this galaxy. We have also studied in detail the circumnuclear and disk emission of the Arp 245 system, and reproduced the FIR SEDs of these two regions with dust models, from which we derived dust temperatures and masses. Our major results are as follows:

- The ground-based  $11.2 \mu\text{m}$  image of NGC 2992 has an angular resolution of  $0.32''$  (55 pc) and reveals faint extended emission along  $PA \sim 30^\circ$  and out to  $\sim 3$  kpc. The orientation of this extended emission coincides with the semi-major axis of the galaxy.
- The GTC/CC spectrum of the faint MIR extended emission clearly shows the  $11.3 \mu\text{m}$  PAH feature and the  $[S\text{ IV}]\lambda 10.5 \mu\text{m}$  emission line once we remove the AGN contribution. Therefore, we conclude that this extended emission is produced, at least in part, by dust heated by star formation. Moreover, by comparing the extended and nuclear spectra of the galaxy we conclude that either the PAH features have been destroyed in the inner  $\sim 50$  pc of NGC 2992, or are diluted by the strong AGN continuum.
- The GTC/CC and Gemini/MICHELLE nuclear spectra of NGC 2992, which probe the inner  $\sim 50$  pc of the galaxy, are identical in spite of the time difference between the observations ( $\sim 7$  years) and the different slit orienta-

tions. These spectra show  $[S\text{ IV}]\lambda 10.5 \mu\text{m}$  emission and no PAH features. This similarity indicates that the X-ray and IR variability previously observed in this galaxy may have stopped after 2007.

- We modelled the nuclear IR SED of NGC 2992 with clumpy torus models, and derived an AGN bolometric luminosity of  $L_{bol}^{AGN} = 5.8 \times 10^{43} \text{ erg s}^{-1}$ , consistent with the value estimated from X-ray data:  $L_{bol}^{X-ray} = 3.2 \times 10^{43} \text{ erg s}^{-1}$ . We infer a small torus radius of  $\sim 1.2$  pc from the fit, a torus mass of  $M_{torus} = 9 \times 10^4 M_\odot$  and a column density of  $N_H = 3.4 \times 10^{24} \text{ cm}^{-2}$ . The latter value is consistent with the range reported from X-ray observations of the inner  $\sim 3$  pc of the galaxy.

- T We calculated nuclear fluxes for NGC 2992 using the Spitzer MIR and Herschel FIR images and different methods, and we found that we can only recover the nuclear fluxes obtained from high angular resolution data at  $20\text{--}25 \mu\text{m}$ , where the AGN emission dominates.

- We decomposed the  $5\text{--}30 \mu\text{m}$  Spitzer/IRS spectrum, which probes the inner 630 pc of NGC 2992, in AGN and SB components. We found that the SB component dominates the MIR emission at  $\lambda \lesssim 15 \mu\text{m}$ , with  $\sim 60\text{--}70\%$  contribution at  $6 \mu\text{m}$ . At  $\lambda \gtrsim 15 \mu\text{m}$ , the AGN component dominates, reaching 90% at  $20 \mu\text{m}$ , and decreasing rapidly at  $\lambda > 30 \mu\text{m}$ .

- The scaled AGN template derived from the spectral decomposition of the Spitzer spectrum agrees well in flux and shape with the GTC/CC nuclear MIR spectrum within the errors, proving the reliability of this method for estimating the SB and AGN contribution to the MIR emission.

- The MIR-to-FIR total SEDs of the interacting galaxies NGC 2992/93 are practically identical in shape and flux. This similarity is likely related to the presence of intense SF in both galaxies, which is heating the dust at similar temperatures.

- We reproduced the FIR emission of the different components of the Arp 245 system using dust models and measured practically the same dust masses, temperatures and SFRs for NGC 2992/93. These measurements are very similar to those reported for non-active interacting systems in the first stages of the interaction.

- The MIR-to-FIR maps and cold dust properties presented here are consistent with the Arp 245 system being in an early stage of the interaction between the galaxy pair NGC 2992/93, with the SF activity mostly concentrated in their circumnuclear regions. On the other hand, the tidal features do not seem to have reached the conditions to be active star forming sites.

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